DIAMETER GROWTH AND WOOD PROPERTIES OF 14-YEAR-OLD LOBLOLLY PINE (*Pinus taeda* L.) IN RELATION TO STAND DENSITY AND CLIMATE

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The general objective of forestry is to grow trees efficiently for various purposes but the ultimate goal of most silviculture is wood production. For successful growth trees require adequate inputs both from environment and genetic factors which have a strong impact on the tree growth and survival. These factors regulate physiological and biochemical processes at the whole plant level and at the cellular level that determine the quality and quantity of growth (Kramer, 1987; Teskey et al., 1987).

Forest productivity is limited most often by environmentally-induced stress, primarily due to lack of water availability and unfavorable temperature. This is notable because most growth and metabolic activities are reduced when high internal moisture stress is prevalent. Water availability, temperature, and concentration of carbon dioxide are expected to change significantly in the future (Gates, 1990; Sampson, 1988; Woodman and Furiness, 1988; Miller et al., 1987). Thus, the impact of these unfavorable environmental conditions on forest productivity should be clearly understood and articulated.

Lack of available water induces the development of internal water deficits and inhibits physiological processes more often than any other single factor (Kramer, 1986; Kramer and Kozlowski, 1960). The effect of water scarcity is more pronounced on cambial activity than on photosynthesis (Brix, 1972). However, trees will only experience the detrimental effects of water deficit stress when it reaches a level where water availability is inadequate and a negative effect on both morphological and physiological processes is created (Teskey and Hinckley, 1986). It has been suggested that these unfavorable environmental conditions could impose detrimental effects and hamper the successful growth of highly commercialized loblolly pine (Pinus taeda L.) in the southern forest of the United States (Miller et al., 1987). Woodman and Furiness (1988) speculated that the production of timber from this region could be severely affected by the projected prolonged high temperature and droughts due to the effect of global warming.

Concerns about atmospheric effects on forest productivity and species composition have been expressed by forest industry in recent years. Evidence from earlier studies indicated that water deficit stress triggered by high evaporative demand had a great influence on wood quality and growth of forest stands (Cregg et al., 1988; Bassett, 1964). It reduced the width of the latewood band and ring latewood percentage, reduced the cell wall thickness and lowered the specific gravity. Prolonged water deficit will cease cambial activity and thus forest productivity because it suppresses the trees drastically and reduces the rate of diameter growth. Water deficit stress also has a profound effect on the allocation of carbon between the shoots and roots (Teskey and Hinckley, 1986). More carbon was partitioned to the roots at the expense of stem growth which was considered as a loss of aboveground productivity.

The severity of water deficit stress can be minimized by improving the soil water status through manipulation of stand density (Stogsdill et al., 1992; Cregg et al., 1990; Cregg et al., 1988; Aussenac and Granier, 1987). Removal of undesired and uneconomical trees by systematic thinning operations results in modification to microclimatic conditions that influence the ecophysiological functioning of trees. Thinning has an impact on the status of the soil water reserve which results in the introduction of a strong heterogeneous spatial distribution of water reserves (Aussenac and Granier, 1987). Harms and Lloyd (1981) noted that stand spacing affects the quality and quantity of wood produced. The reduction of basal area by thinning, which also alters stand structure, creates a more conducive microenvironment for growing which in turn increases tree radial growth (Cregg et al., 1990; Aussenac and Granier, 1988). This is mainly attributed to an increase in soil water availability, more growing space and redistribution of stand growth to better species.

Studies on the effects of water deficit stress on tree growth and wood quality at diameter breast height (DBH) showed that thinning consistently delayed the inception of latewood (Cregg et al., 1988; Brix and Mitchell, 1980). However, the ring latewood percentage and specific gravity were not significantly affected by thinning (Cregg et al., 1988). Individual tree basal area could be increased by reallocation of soil moisture, nutrients, and reduced competition among trees without reducing wood quality. In a thinning and pruning study, Zahner and Oliver (1962) indicated that the initiation of latewood of jack pine (Pinus banksiana L.) differed significantly between bole positions at DBH and at the base of live crown (BLC). However, in red pine (Pinus resinosa Ait.) the changeover from earlywood to latewood occurred about the same time at both DBH and BLC.

Wood is not only the most massive reproducible biological product of the cambium but also the most valuable economic product of the tree. Water scarcity affects cambial activity but the production of photosynthate is strongly influenced by environmental factors. This implies how critical the plant water balance is in controlling physiological processes and conditions which in turn determine the wood properties.

Studies on the effect of water stress on the growth of loblolly pine at DBH have been well documented. However, the information pertaining to the growth and wood quality at higher bole positions are still lacking. This study will investigate the effect of precommercial thinning and environmental conditions on wood formation within the bole of a 14-year-old loblolly pine plantation in southeastern Oklahoma. The effects of thinning on wood properties at DBH at the same study site have been reported in detail by Cregg et al. (1988).

The objectives of the present study are to (1) quantify the initiation date of latewood formation at three different bole heights for a wide range of basal areas (2) determine the effects of thinning on ring latewood percentage, and (3) understand the relationship between tree growth , environmental and physiological variables, and wood quality.

CHAPTER II

MATERIALS AND METHODS

Site Description

The study was established in 1986 as part of the Long Term Loblolly Pine Intensive Forest Ecosystem Research (LTLPIFER) project located in southeastern Oklahoma near Eagletown. Details of the site have been described by Cregg et al. (1988). The soil of this area is the Cahaba series of the Guyton-Ochlockonee association, and the texture ranges from loam to silty loam (USDA SCS, 1974). These soils are poorly drained to well drained with slopes of less then one percent on the flood-plains and terraces of the Mountain Fork and Little Rivers.

The region's climate is characterized by mild to hot temperature and irregularly distributed annual precipitation with a high frequency of severe summer droughts. The average annual precipitation is 120 cm and the mean annual temperature is 17 ^{o}C (Climate Normals for the U.S., Base:1951-80, 1983). The average frost-free period of the region is 240 days (Oklahoma Water Resources Board, 1984). The on-site soil moisture holding capacity of the 0-122 cm profile was determined to be 22.8 cm (Stogsdill et al., 1992).

Following site preparation in 1975, the area was planted with an unimproved seed source of loblolly pine at a stocking density of approximately 2500 trees per hectare (Cregg et al., 1988). The mean basal area of the selected 1.3 ha study area was 25.9 m^2ha^{-1} and the overall vigor of the stand was satisfactory.

Study Design

The experimental design of the present study has previously been described in detail by Cregg et al. (1988). In April 1984, a randomized complete block thinning study was established with three 0.1-ha treatment plots assigned at random to each of three blocks. Five trees were randomly selected on each treatment plot giving a total of 15 trees per treatment. The three treatment levels were BA 25 (25 ft^2ac^{-1}, 5.8 m^2ha^{-1}), BA 50 (50 ft^2ac^{-1}, 11.5 m^2ha^{-1}), and BA 100 (unthinned, 100 ft^2ac^{-1}, 23 m^2ha^{-1}). The treatment plots were thinned from below to improve mean individual tree size and form, and to preserve uniform spacing. Felled trees were not removed from the site and understory vegetation was not controlled. The stand characteristics at the beginning of the present study for each treatment are listed in Table I. The site's variation was reduced by arranging the plots parallel to the Mountain Fork River approximately 50 meters east of the study site.

TABLE I

STAND CHARACTERISTICS OF TREATMENT PLOTS, SPRING 1986

Treatment	Mean basal area	Mean dbh
	m^2ha^{-1}	cm
BA 25	12.15	19.04
BA 50	18.02	18.67
BA 100	32.49	16.95

Environmental Measurements

Monthly summaries of weather data for the region were obtained from National Oceanic and Atmospheric Administration records from the U.S. Army Corps of Engineers' weather station at Broken Bow Dam, about 27 km from the study site. The on-site precipitation was monitored with two standard rain gauges.

Soil moisture on the site was measured using the same techniques adopted by Cregg et al. (1988). Each measurement plot was installed with three 3.8 cm diameter steel access tubes to a depth of 122 cm on each plot giving a total of nine tubes per treatment. Volumetric soil moisture content was measured at biweekly interval from May to November in 1986 using a calibrated neutron probe moisture gauge

(Troxler 3223). Neutron counts were taken at 30-cm intervals from 15 cm to a depth of 105 cm. The available soil water was expressed as the percentage of the total available soil water in the 122 cm soil profile.

Growth

A 0.04-ha measurement plot was located inside each 0.1-ha treatment plot to reduce edge effects. Diameters were measured at three bole heights, namely at DBH, at BLC, and at the mid-point between DBH and BLC. BLC was a bole position where the base of the whole live crown is located. A dendrometer band was placed below the lowest live branch of the BLC crown. Thus, the mid-point between DBH and BLC was not consistent among each sampled tree. Dendrometer bands were placed at these positions to monitor seasonal diameter growth of 5 trees selected at random on each measurement plot (Liming 1957). The heights of the dendrometer bands placed at different bole positions and the tree dimensions are shown in Table II.

A ladder was used to reach the dendrometer bands at the middle and BLC positions. Growth was measured from March 25 to November 19, 1986 at biweekly intervals. During the summer drought the measurements were carried out at weekly intervals. The circumference was determined by reading the vernier scale of the dendrometer bands. These measurements were then converted to diameters for analysis.

TABLE II

BOLE DIAMETER AND HEIGHTS OF DENDROMETER BANDS FOR EACH THINNING TREATMENT AND BOLE POSITION

Treatment	Bole position	Mean bole diameter	Mean Dendrometer heights
		cm	m
BA 25	DBH	18.64	1.43
	Middle	17.50	2.87
	BLC	15.55	4.35
BA 50	DBH	18.49	1.42
	Middle	16.80	3.03
	BLC	14.99	4.69
BA 100	DBH	15.92	1.42
	Middle	13.98	3.42
	BLC	11.84	5.41

Wood Core Analysis

Wood samples of each tree were extracted from the outer annual ring at each position on the bole using an increment hammer. A total of eight samples per bole position were obtained at approximately 7 - 21 day intervals from June 9, 1986 to January 15, 1987. Each core was kept in a vial containing a 1:1 mixture of alcohol and water as preservative (Cregg et al., 1988). A total of 1080 samples were kept in individual vials until 1991 when the cores were examined.

The long duration of storage had a negative effect on some of the samples. In these cases, the color of the samples became too dark to visualize the color of earlywood and latewood. A few of the samples were moulded, and slightly more than 20% of the samples were dried and easily broken into small pieces, especially during the slide preparation. These samples were unreliable for specific gravity determination. However, after rehydration these samples still could be used for determining the transition dates from earlywood to latewood.

The transition dates of latewood from earlywood were estimated by microscopic examination. Wood cores that were sampled from June 9, 1986, to August 25, 1986, were analyzed to determine the transition dates for the 1986 growing season. These samples were extracted at eight to thirteen day intervals. Each sample was hand-sectioned by making a cut against the wood rays and mounted to the slide. A calibrated light microscope was used to observe the presence of latewood based on Mork's definition of latewood cells as described by Kozlowski (1971). The presence of both earlywood and latewood cells could be easily identified under the microscope (Cregg et al., 1988). However, these tracheids can only be clearly seen on a transverse plane provided the sectioning was correctly done. Hence, the wood sectioning process was critical in ensuring the visibility of latewood cells. Some of the cores did not have a uniformly shaped latewood band and often the boundary between the earlywood and newly formed latewood was not straight. In such a situation a few measurements were made to get the average width of the latewood band.

The date of the latewood initiation was established at the time when the entire cross-section of new wood was occupied by latewood cells. Two latewood band measurements from two different julian dates were needed to estimate the transition date. The difference between these two measurements was compared to the growth rate shown on the dendrometer bands to calculate the number of days of latewood production and subsequently the date of latewood transition (Cregg et al., 1988).

The final core sampling was done at the end of the growing season and was used to determine the ring latewood percentage. These cores were hand-sectioned and mounted on the slide. An eye-piece micrometer was used to quantify the width of the latewood band. This technique was employed primarily because of the difficulty in visually differentiating the color of the latewood and earlywood. The width of latewood band within the total annual ring width was entered into equation 1 to quantify the latewood percentage.

$$\text{Percent latewood} = \frac{\text{Width of latewood band}}{\text{Total ring width}} \tag{1}$$

Statistical Analysis

An analysis of variance and GLM procedure for a randomized complete block design from the Statistical Analysis System (SAS, 1985) were employed to determine the differences in wood properties between the bole heights within and between the treatments. Duncan's Multiple Range Test was used to develop the multiple comparisons of treatment means of latewood transition dates, percentage of latewood within the annual ring, and tree growth. Differences within and between the treatments were judged to be significant when $p<0.05$.

CHAPTER III

RESULTS AND DISCUSSION

Environment

Monthly rainfall and temperature for 1986 and the climate normals (means for 30 year period, 1951-1980) at Idabel, Oklahoma are presented in Table III. The differences between the two periods indicate that 1986 was a relatively dry year with low precipitation and slightly higher temperature than the climate average. The seasonal temperature, precipitation and pan evaporation (evaporation from a free-water surface) at Broken Bow Dam, Oklahoma for 1986 are shown in Figure 1.

The total amount of rainfall at Broken Bow Dam in 1986 was 1101 mm recorded from 89 rainy days. Rainfall from the beginning of May to end of October totaled 584 mm from 46 rainy days but only three rainfall events of 30 mm or more occurred during this period. A dry summer period in 1986 was observed from early May to late August (Figure 1). Although 27 rainy days were recorded throughout this period with rainfall totaling 338 mm, pan evaporation remained high and exceeded precipitation. The most severe atmospheric moisture demand was observed from mid-June to end of August when the average temperature was 22.23 ^{o}C (Figure 2).

During this period the total pan evaporation was 583 mm while the total precipitation was 152 mm. The detrimental effects of high evaporative demand on tree growth was observed from Julian date 181 (June 30) to Julian date 216 (August 4), and from Julian date 223 (August 11) to Julian date 237 (August 25). Three rainfall events totaled 46 mm from Julian date 218 (August 6) to Julian date 223 which offset the continuation of the high evaporative demand of the 1986 growing season (Figure 2). The climate pattern is similar to that observed in 1985 by Cregg et al. (1988).

TABLE III

MONTHLY RAINFALL AND TEMPERATURE FOR 1986 COMPARED TO MEANS FROM 30 YEARS, AT IDABEL, OKLAHOMA

Month	Precipitation			Temperature		
	Normal	1986	+/-	Normal	1986	+/-
	..... mm			......°C		
January	77	11	-66	5.6	7.1	+1.5
February	87	99	+12	7.9	10.2	+2.3
March	111	46	-65	12.2	13.7	+1.5
April	137	164	+27	17.3	18.3	+1.0
May	144	107	-37	21.4	20.6	-0.8
June	94	112	+18	25.5	25.8	+0.3
July	90	56	-34	27.7	28.7	+0.1
August	67	63	- 4	27.4	26.6	-0.8
September	115	141	+26	23.8	24.6	+0.8
October	98	105	+ 7	17.8	17.7	-0.1
November	97	132	+35	11.4	10.4	-1.0
December	88	65	-23	7.2	6.4	-0.8
Total	1205	1101	-104	17.1	17.5	+0.4

+/- = 1986 - Normal

Available Soil Water

The available soil water decreased rapidly following the onset of the high evaporative demand period (Figure 3). Throughout the growing season, the thinned treatments consistently displayed a higher soil water content than the unthinned treatment. The longest rainfree period was recorded for 19 days in July (Julian date 183 to Julian date 202) but the available soil water reached its lowest level on the first week of August. Three rainfall events that totaled 46 mm during the middle part of August allowed the soil to maintain its water level and subsequent rainfalls further improved the soil water availability.

Results from earlier studies at the same study site produced a similar available soil water pattern. Stogsdill et al. (1992) observed that thinning was more effective on reducing the soil water depletion during 1984, a relatively wet year, than during 1985, a year of low summer rainfall. The estimated water use rates during the dry year were about 40% less than the estimated water use in a wet year due to lower growing season rainfall. Cregg et al. (1988) reported a similar trend where the soil water potential for the top 120 cm soil profile was significantly lower in 1985 compared to 1984. It was also observed that tree water deficit stress was greatest when the soil moisture availability was low. From the same study, Cregg et al. (1990) observed that at each year, thinning had a significant effect on soil water potential during the dry period. Following thinning, the available soil water was consistently higher on thinned plots than on unthinned plots due to the effect of throughfall precipitation and decreased evaporation. Although the effect of thinning on xylem water potential was not consistently significant, the annual variation in xylem water potential was apparent.

Bole Growth

The effects of water deficit stress on the tree growth was observed approximately four weeks after the onset of the soil water depletion (Figures 4 to 9). The detrimental effects of high evaporative demand on diameter growth coincided with the severe soil depletion period that occurred from July 7 (Julian date 188) to August 5 (Julian date 217). During this period the overall daily growth rates for the thinning treatments and at bole positions were drastically reduced ranging from 50% to more than 80% from the mean daily growth rate of the 1986 growing season.

The overall daily growth rate, diameter growth and per tree cross-sectional area differed significantly between all the treatments and bole positions with the BA 25 treatment and DBH displaying the most gain. Cross-sectional surface area on the BA 25 and BA 50 plots increased by 185% and 108% respectively, relative to the BA 100 treatment. Treatment, bole position and treatment-bole position interaction effects were significant for all the growth parameters observed.

Greater daily growth rate averages were observed in trees on thinned plots compared to trees on unthinned plots with 0.07 mm day^{-1} for BA 25, 0.05 mm day^{-1} for BA 50 and 0.03 mm day^{-1} for BA 100, respectively (Table IV). Similarly, during the severe water depletion period the overall daily growth rate for BA 100 was markedly reduced to 0.005 mm day^{-1} compared to 0.02 mm day^{-1} and 0.01 mm day^{-1} for BA 25 and BA 50, respectively. The differences between the growth rate of all the treatments measured at different bole positions were significant. It was observed that the growth rates of the BA 25 and BA 50 treatments were severely affected by the high evaporative demand. However, trees on these plots grew at a faster rate than trees on the unthinned plots once the environmental factors were favorable (Figures 10, 14, 15 and 16).

Similarly the daily growth rate at individual bole positions was significantly different. The greatest daily growth rate was measured at DBH, followed by BLC, and the middle of the bole position with 0.06 mm day^{-1}, 0.05 mm day^{-1}, and 0.04 mm day^{-1}, respectively (Table IV). However, the growth pattern changed during the severe water depletion period where a greater daily growth rates occured at both the middle and BLC positions compared to DBH with 0.02 mm day^{-1} and 0.01 mm day^{-1}, respectively. The reversal trend implies that bole growth at DBH was more sensitive to high evaporative demand compared to other bole positions. Daily growth rate was in a decreasing fashion for the majority of the trees during the period of high evaporative demand (Figures 10 and 11). The reversal trend was observed in response to rainfalls from Julian date 218 to Julian date 223, but the daily growth rate decreased rapidly after that period until Julian date 237.

The most bole growth was observed at DBH and the least was at the middle of the bole position. Within the treatments, BA 25 displayed the most diameter growth and the least was BA 100. The trees on the unthinned plots have a slower growth for a longer period of time compared to the trees on the thinned plots (Figure 12). Figure 13 shows that the cumulative growth pattern at the middle of bole position and at BLC are similar but slower than growth at DBH. The bole growth at DBH of the BA 100 treatment was severely affected by water deficit stress compared to other bole positions. During the period of severe moisture depletion, the bole growth at DBH of the BA 100 treatment shrunk for twenty days longer (Julian date 189 to Julian date 216) than growth at the same bole position for trees on the BA 50 plots, and at the middle bole position for trees on the BA 100 plots (Julian date 209 to Julian date 216). No single tree at BLC in all the treatments was shrunk but no measurable bole growth was observed during this period (Figures 12 and 13). Figures 14 to 19 show the response of bole positions and individual treatment to precipitation and pan evaporation during the growing season of 1986.

TABLE IV

MEAN GROWTH RATE, DIAMETER GROWTH AND PER TREE CROSS-SECTIONAL SURFACE AREA FOR EACH TREATMENT AND BOLE POSITION

Treatment/Position		Growth rate	Diameter growth	Cross-sectional surface area
		mm day^{-1}	cm	cm^2
Treatment	BA 25	0.07a	1.33a	42.31a
	BA 50	0.05b	0.82b	30.96b
	BA 100	0.03c	0.57c	14.85c
Position	DBH	0.06a	1.33a	50.54a
	Middle	0.04c	0.61c	16.85b
	BLC	0.05b	0.78b	20.73b

Within the columns, means with the same letter are not significantly different at P = 0.05. N = 45.

The pattern of growth response to thinning and water deficit stresses at DBH is consistent with most thinning studies (Ginn et al., 1991; Marquis et al., 1991; Cregg et al., 1988; Zahner and Whitmore, 1960). Zahner and Oliver (1962) reported more growth at BLC than at DBH due to greater number of large diameter cells and prolonged production of these type of cells. In another study on Douglas-fir (Brix, 1972), greater radial increment was observed at one-half tree height than at DBH. In contrast, results from the present study indicate that the most diameter growth was observed at DBH, followed at BLC, and finally at the middle of the bole. All the treatments displayed similar growth pattern. The variation in the pattern of diameter growth is influenced by the availability of carbohydrate and by the result of the allocation of this substance in the tree (Smith, 1986).

Cambial activity is directly affected by the availability of water which determines the movement of auxins and carbohydrates to the cambial region for wood production (Teskey et al., 1987; Zahner, 1963). Cambial activity is reduced during summer when soil moisture becomes a major limiting factor to the cell expansion (Kramer, 1964; Zahner, 1963). The cessation of bole growth and stem shrinking are mainly because the cambial initial activity is affected by hydration of bark stem tissues and lack of carbohydrate in the cambial region (Cregg et al., 1988; Megraw, 1985; Zahner, 1963). Most of the shrinkage was observed to be localized in the cambial zone and was found to be strongly correlated with diameter growth (Kramer and Kozlowski, 1979; Fritts, 1956).

Latewood Transition Date

The date of transition from earlywood to latewood was affected by both the treatment and stem position effects but not by the interaction of these parameters. Table V shows that there was a significant difference between the transition date in the thinned and unthinned treatments. Overall, the transition date for trees on unthinned plots was seven to eight days earlier than for trees on the thinned plots.

TABLE V

MEAN LATEWOOD INITIATION DATE BY STAND DENSITY AND BOLE POSITION

Treatment/Position		Latewood initiation date
Treatment	BA 25	June 30a
	BA 50	June 29a
	BA 100	June 22b
Position	DBH	June 21a
	MIDDLE	June 28b
	BLC	July 2c

Means followed by the same letter for each treatment and position are not significantly different at P = 0.05. Each treatment and bole position mean are pooled separately. N = 45.

The initiation of latewood cells was significantly different at all the bole positions (Table V). For all thinning treatments the transition date was earliest at DBH, followed by at the middle and BLC positions. The date of transition occurred seven to eleven days sooner at DBH than at the middle bole positions and at BLC, respectively.

Table VI shows the mean date of latewood initiation for the thinning treatments at individual bole positions. The development of the latewood band for all 45 trees required over four weeks at both DBH and at the middle of bole position compared to over three weeks at BLC. The smallest range was 18 days at BLC and the largest was 45 days at DBH and both occurred in the BA 25 treatment.

For the BA 25 treatment, the initiation of latewood cells at DBH occurred 6 to 16 days earlier than at the middle and at the BLC, respectively. For the BA 50 and BA 100 treatments, the transition date at DBH was 6 to 11 days and 9 to 14 days sooner than at the middle and at the BLC positions, respectively. Only small differences between BA 25 and BA 50 were found. However, the differences were consistently greater between the thinned and the unthinned treatments.

Figure 20 shows the cumulative percentage of trees past the latewood initiation date at different bole heights. The initiation of latewood cells was first observed at DBH around June 4 (Julian date 155), about seven to nine days earlier than at the middle and at the BLC levels. More than 90 percent of the trees initiated latewood at DBH by July 2 (Julian date 183). The development of latewood cells at both DBH and at the middle bole positions was completed by July 6 (Julian date 187). At BLC, the same percentages were not reached until July 12 (Julian date 193) and July 20 (Julian date 201), respectively.

TABLE VI

MEAN LATEWOOD INITIATION DATE AT DIFFERENT BOLE HEIGHTS FOR THE BA 25, BA 50 AND BA 100 THINNING TREATMENTS

Bole Height	BA 25	BA 50	BA 100
DBH	June 25a	June 23a	June 14a
Middle	July 1b	June 29ab	June 23b
BLC	July 5b	July 4b	June 28b

Within the same columns, means followed by the same letter are not significantly different at P = 0.05. N = 15.

Results of the mean latewood initiation date at DBH are in agreement with results from other thinning studies (Cregg et al., 1988; Axelsson and Axelsson, 1986; Brix, 1972; Bassett, 1964; Zahner and Oliver, 1962). In a thinning study at this same location (Cregg et al., 1988), the transition date at DBH for all treatments was June 25 (Julian date 176). The wood core analysis for the present study indicated that the mean transition date for all treatments and bole positions was June 27 (Julian date 178), whereas the mean transition date for thinned treatments and bole positions was June 29 (Julian date 180). The initiation of latewood cells occurred within the first one third of the growing season of 1986. In Cregg's study the trees on the unthinned plots initiated latewood cells a week and one half to two weeks sooner than trees on the thinned plots. The same pattern of latewood development was observed in the present study. Results shown in Table VI on initiation of latewood cells at DBH and BLC are similar with results obtained from a thinning and pruning study on red pine (Zahner and Oliver, 1962). In the present study, the transition date at the middle and BLC occurred 4 days and 13 days after that at DBH, respectively.

Hormonal, phenology, and environmental factors have been cited as potential factors that have a strong bearing on the mechanisms controlling the development of latewood cells (Zahner, 1963; Larson, 1960). Larson (1962) indicates that both environmental and tree crown factors have an indirect effect on the formation of latewood cells. Larson (1962) further speculated that the onset of these cells was influenced by the reduction in auxin synthesis due to cessation of foliar growth that promotes a longer accrual period of the wall thickening process. It was reported that the initiation of latewood cells coincide with the completion of terminal growth and the time when the year's new needles become a source of photosynthate export (Megraw, 1985; Panshin and de Zeeuw, 1980; Larson, 1969).

The availability of photosynthetic products due to the rise of photosynthesis activity could be the most critical factor to the formation of latewood cells. The distance from the source of auxin and translocation of auxin from the active region of crown foliage through lateral and downward translocations influenced the timing of the formation of latewood cells at different stem heights (Megraw, 1985; Panshin and de Zeeuw, 1980). Lack of water curtails the transport and availability of carbohydrate for wood formation (Whitmore and Zahner, 1966; Zahner, 1963). The combination of reduction in auxin synthesis and slower translocation rates results in less auxin reaching the base of the tree. This explains why latewood cells first occur at DBH and gradually proceeds upward.

Auxin availability is not the sole factor that triggers the formation of latewood cells. The initiation of these cells is also strongly influenced by weather and silvicultural practices such as thinning (Cregg et al., 1988; Whitmore and Zahner, 1966; Zahner, 1963; Zahner and Oliver, 1962). The severity of water deficit stress has a strong impact on the movement of auxins, partitioning of photosynthate, cambial activity and other physiological processes in trees (Cregg et al., 1988; Teskey et al., 1987; Zahner, 1963).

The growth response to internal water deficits was reported to be different between stem positions (Zahner, 1963; Zahner and Oliver, 1962; Smith and Wilsie, 1961). Greater cambial activity of loblolly pine was observed at the upper stem position than at the lower stem position during the dry years but the reverse was observed during low water deficit periods (Smith and Wilsie, 1961). Zahner and

Oliver (1962) indicated that thinning significantly affects the transition date of jack pine at different stem positions. The delay in the transition from earlywood to latewood at different bole heights was interpreted to be due to the influence of auxins, crown conditions, the distance of bole position from the crown, the assimilation and translocation of photosynthate, and the lack of turgor in the xylem-cambium region (Zahner, 1963; Zahner and Oliver, 1962).

Results from the present study show that the pattern of the latewood initiation date at three different bole heights is consistent with the speculation of the effect of water stress on the production and translocation of auxins and photosynthate in trees. The transition date at all bole positions in both the thinned treatments was delayed as compared to trees on unthinned plots. This study reemphasizes that the variation in the initiation of latewood cells was related to the thinning treatments that change the crown microenvironment and function, and soil water availability for residual trees.

Latewood Percentage

The differences in the overall mean latewood percentage for both thinning treatments and stem positions are not significant (Table VII). Mean treatment latewood percentage was greatest in the BA 50 treatment and least in the BA 100 treatment. Within the bole positions, the greatest latewood percentage was observed at DBH followed by at the middle and at BLC.

TABLE VII

MEAN LATEWOOD PERCENTAGE BY THINNING TREATMENT AND BY BOLE POSITION

Treatment/Position		Latewood Percentage
Treatment	BA 25	33.3a
	BA 50	34.4a
	BA 100	30.8a
Position	DBH	34.8a
	Middle	32.8a
	BLC	30.8a

Means followed by the same letter are not significantly different at P = 0.05.

Figure 21 shows the mean latewood percentage at individual bole positions. At DBH the greatest percentage of latewood was produced in BA 100. Both the middle and BLC positions produced similar pattern. However, at BLC the difference between the thinned treatments and unthinned treatment was more distinct than at the middle bole position.

Figure 22 illustrates the mean latewood percentage of the thinning treatments at different stand densities. Differences among bole positions for BA 25 and BA 50 were relatively small. In contrast, a large difference was observed between DBH and BLC positions of BA 100.

Table VIII shows the effect of thinning on the latewood percentage at different bole positions. The latewood percentage of individual treatments at DBH and at the middle bole positions were not significant. The effect of water deficit stress was more apparent at BLC where the difference between BA 50 and BA 100 was significant. Although differences among bole positions for BA 25 and BA 50 were not detected, a difference between DBH and BLC positions for BA 100 was observed (35.41% versus 26.90%, $p = 0.05$).

Results at DBH are consistent with the earlier thinning study by Cregg et al. (1988) where trees on the BA 100 plots produced the greatest latewood percentage. However, at this stem position thinning does not influence the percentage of latewood (Cregg et al., 1988; Brix and Mitchell, 1980; Zahner and Oliver, 1962). In the present study, the low overall mean latewood in the BA 100 treatment is possibly due to the low latewood percentage at the higher bole positions (Table VIII). This implies that at the BLC position of the unthinned treatment, the tendency to produce less dense and weaker wood is greater than trees on thinned plots. Results from this study support the evidence that thinning does not produce weaker wood (Cregg et al., 1988; Megraw, 1985).

TABLE VIII

MEAN LATEWOOD PERCENTAGE OF BA 25, BA 50, AND BA 100 TREATMENTS AT DIFFERENT BOLE HEIGHTS

Treatment	DBH	MIDDLE	BLC
BA 25	34.12a	33.23a	32.47ab
BA 50	34.80a	35.90a	33.33a
BA 100	35.41a	30.54a	26.90b

Within columns, means followed by the same letter are not significantly different at $P = 0.05$.

Thinning reduces the internal water deficit stress in trees by increasing soil water availability primarily due to less competition for water. This allows crown and cambial activity for a longer period and thus delays the production of latewood (Cregg et al., 1988; Brix, 1971; Zahner and Oliver, 1962). The production of new wood is determined by the amount of photosynthate and auxin translocated and reaching the cambial region (Zahner, 1963; Kramer, 1962; Larson, 1960). However severe water deficit stress affects the production of new wood due to cessation or slower cambial activity even in the present of auxin (Zahner, 1963).

Megraw (1985) noted that severe summer drought reduced the latewood percentage of 30-year-old loblolly pine. Brix (1972) observed a lower percentage of latewood at one-half tree height than at the breast height of 23-year-old Douglas-fir. He also noted that the severity of water stress and its duration after the initiation of latewood have a strong influence on the percentage of latewood. In another thinning study on red pine and jack pine, Zahner and Oliver (1962) observed that higher percentage of latewood was observed at breast height than at the base of the crown.

In this study, latewood initiation occurred significantly earlier for BA 100 and at DBH, but the latewood percentage among the thinning treatments and bole positions are not significantly different. Information from Figure 6 is useful in explaining this apparent discrepency. This graph shows that throughout the growing season, the cumulative growth for BA 100 was less vigorous compared to the thinning treatments. However, diameter growth at DBH was greater than diameter growth at other bole positions for all the thinning treatments (Figure 5).

Larson (1962) explained that an auxin gradient along the bole was a probable factor that triggered the onset of an early development of latewood cells at DBH. Cregg et al. (1988) noted that delayed latewood initiation on the thinned treatments was compensated by vigorous growth at the later part of the growing season that increased the percentage of latewood. This resulted in no differences between the proportion of latewood produced in both thinned and unthinned treatments. The allocation of photosynthate before and after the latewood initiation could be another factor that influences the proportion of latewood produced (Zahner, 1963). Thus, climate, tree vigor, auxin, and partitioning of carbon are the most probable factors that determine the formation of latewood.

CHAPTER IV

CONCLUSIONS

The growth pattern at different bole positions indicates that the effect of water deficit stress could be minimized by judicious thinning treatments. Larson (1969) stressed the importance of manipulating stand density as a tool for regulating the wood quantity and wood quality. In the present study, greater bole growth was observed on thinned plots at DBH, BLC, and at the midpoint of DBH and BLC than on the unthinned plots. This suggests the direct effect of water scarcity on turgor-dependent mechanisms, primarily on cambial activity and indirectly on the availability of building materials.

The growing season of 1986 was a relatively dry season compared to mean for 30 years period. The soil water availability had reached its lowest level in early August and thinning appeared ineffective during the severe water depletion period. On the stand level, the severity of water scarcity and high temperature effects were more distinct for trees on unthinned stand. Within the bole position, obviously the effects of lack of available water was more pronounced at the lower part of the bole. Slower growth for a longer period on unthinned plots suggests that more time is needed for the trees to recover from the detrimental effects of water deficit stress on the production and allocation of photosynthate.

The transition from earlywood to latewood occurred seven to eleven days sooner at DBH than at the middle, and at BLC positions. Thinning treatments consistently delayed the transition date at all bole positions. This study reemphasizes the model developed by Cregg et al. (1988) on the function of evaporative demand and low soil moisture as the most critical environmental factors that have a strong bearing on the latewood initiation date. Variation in the latewood transition date reflects the impact of environmental stress on carbon fixation and the partitioning of photosynthate in trees. However, the latewood percentage was not markedly affected by thinning treatments. The evidence supports the finding by Cregg et al. (1988) that showing the influence of weather and soil moisture availability on the percentage of latewood. In this study, the effect of water deficit stress during the high evaporative demand was more pronounced at BLC on unthinned plots suggesting lack of building materials at this bole position. Thus, the tendency to produce weaker and lower quality wood is greater at this bole position which is about 5 meters above the ground, or could extend as low as from the midpoint between DBH and BLC.

The results reported in this study reaffirmed the importance of the interaction between silvicultural treatments such as thinning and climatic variation on wood properties. It is imperative to consider these factors when attempting to produce quality wood through manipulation of stand density. However, any effort towards this direction should be made carefully because of complex interaction among the factors involved. Thus, identifying and quantifying the direct and indirect effects of stress on wood properties are of importance to the forest scientists. For the plantation foresters, the results indicate that appropriate stand density is another important factor in silvicultural practices because of its strong influence on tree survival and the size of the trees to be harvested. Undoubtedly, it also has a strong relationship with economic, management, and biological factors that influence the planting cost.

Forest industry is concerned about the deleterious effects of high percentage juvenile wood on strength and performance of wood products. The results from the present study signify the evidence that faster growth rates of loblolly pine do not reduce the quality of wood formed. However, rapid growth rate in a shorter rotation period has a high tendency to produce tree with large diameter but lack of wood properties needed for products requiring structural strength.

This study noted the importance of controlling the stand density and stand structure to ensure that desired growth responses are obtained. A suggestion that can be derived from this study and as suggested by Marquis et al. (1991), Cregg et at. (1988), and Larson (1962) is to delaying the thinning treatment to enhance natural self-prunning. Thinning at an early stage of growth is not necessarily a profitable idea because the trees still have a high percentage of juvenile wood at most of the bole positions. Thinning should be carried out appropriately to increase the production of mature wood.

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APPENDIX

FIGURES

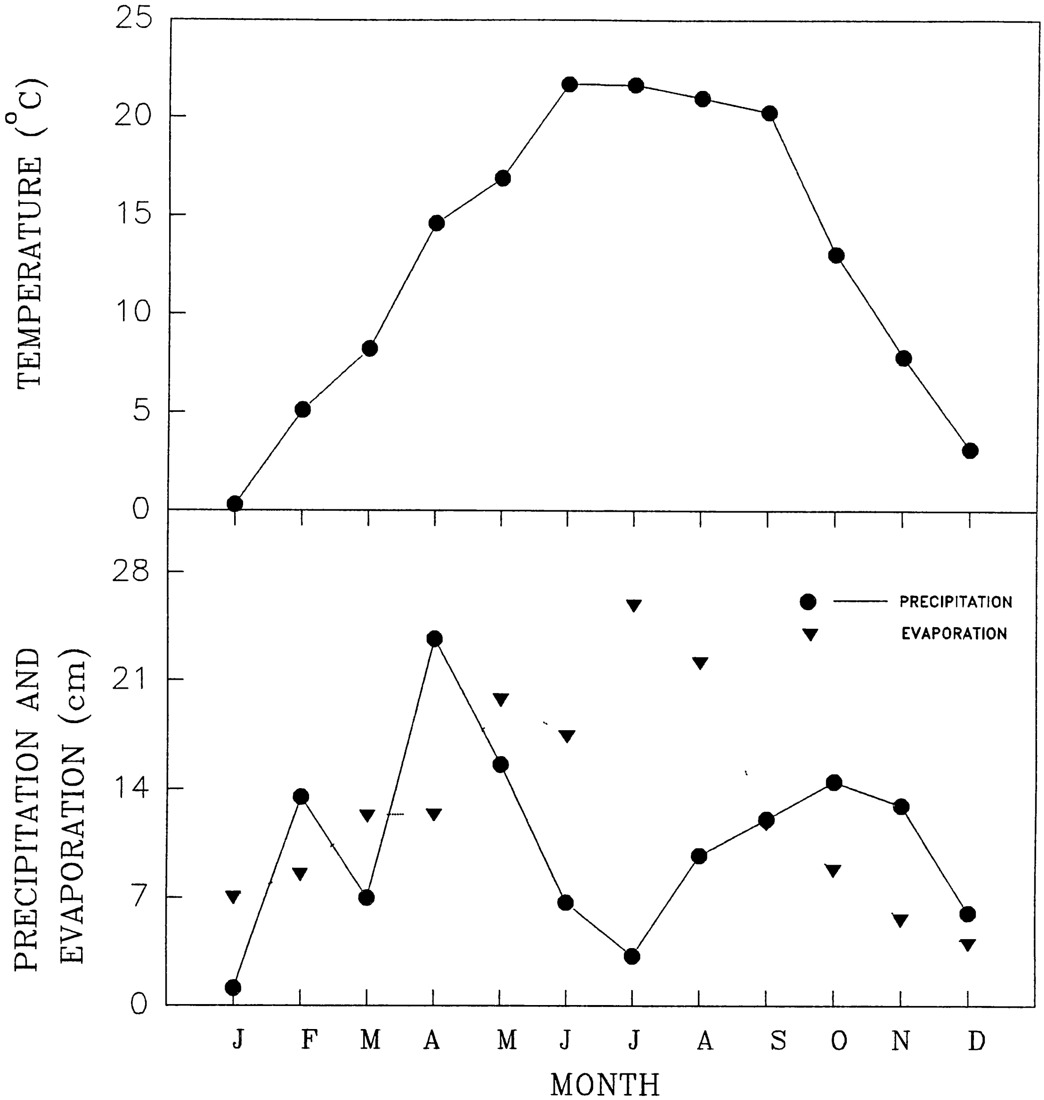

Figure 1 Mean monthly temperature, precipitation and pan evaporation, in 1986, Broken Bow Dam, Oklahoma

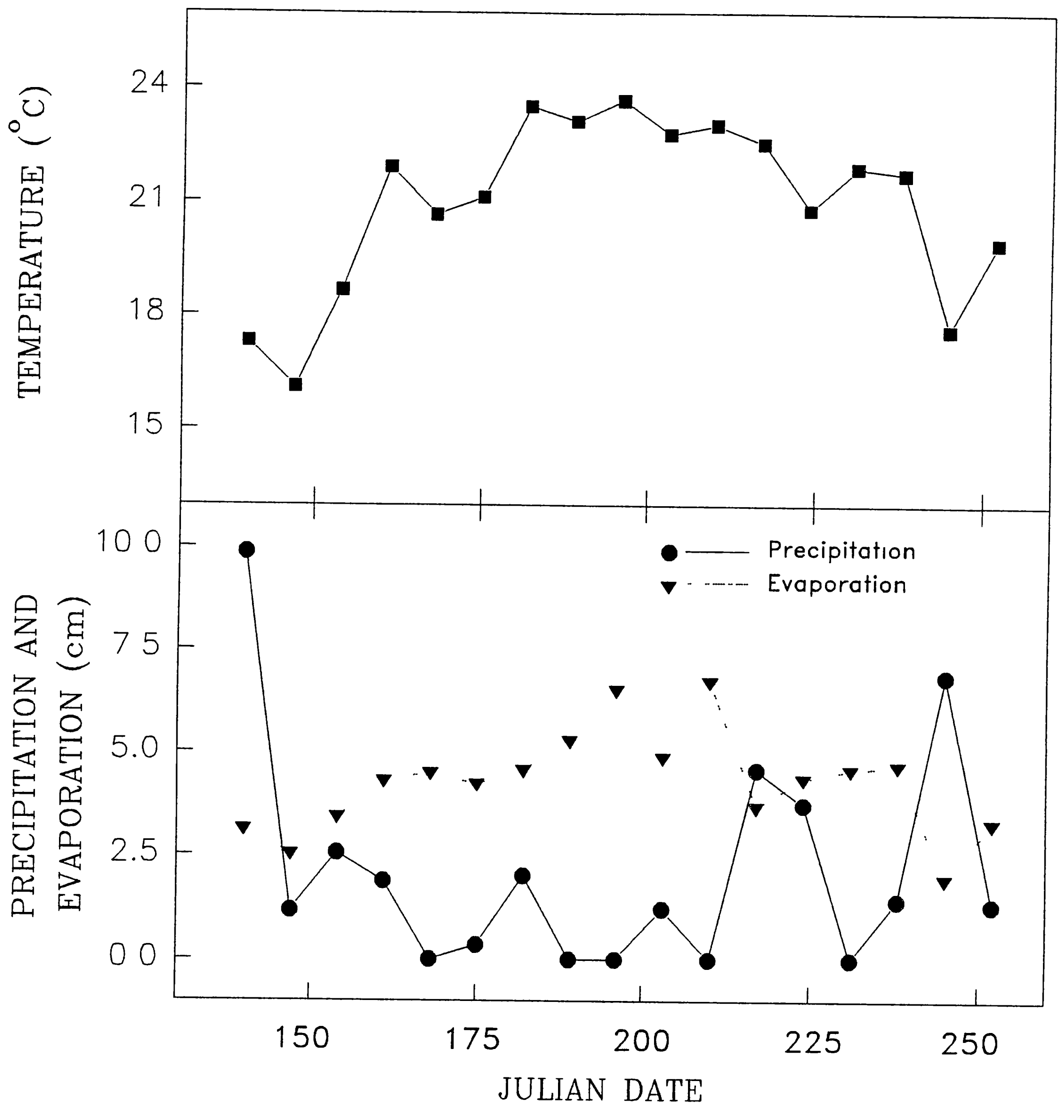

Figure 2. Mean weekly temperature, precipitation and pan evaporation May–September 1986 at Broken Bow Dam, Oklahoma

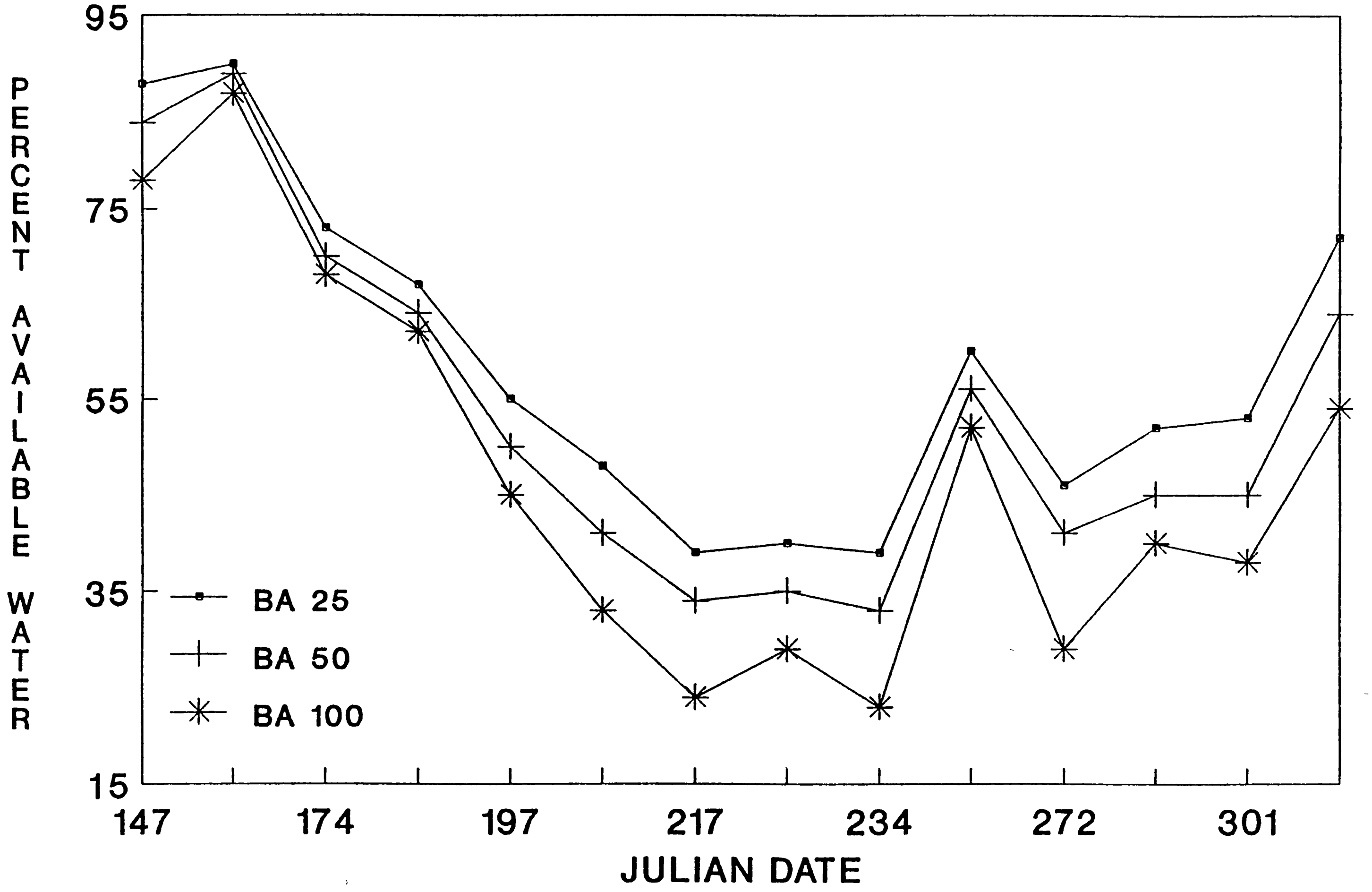

Figure 3. Mean percent available water at top 107 cm soil profile, in 1986.

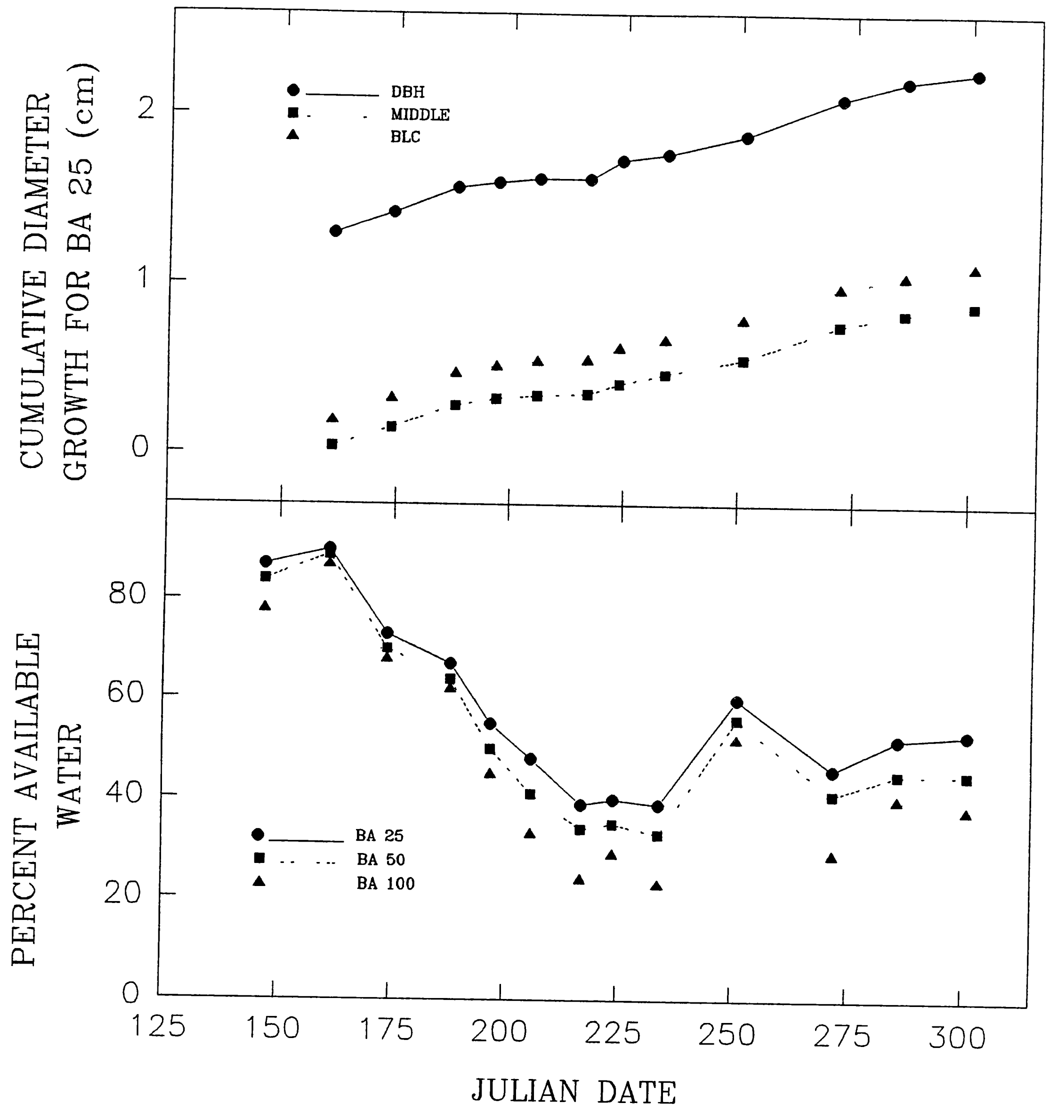

Figure 4 Percent available water and cumulative mean diameter growth of BA 25 at different bole heights

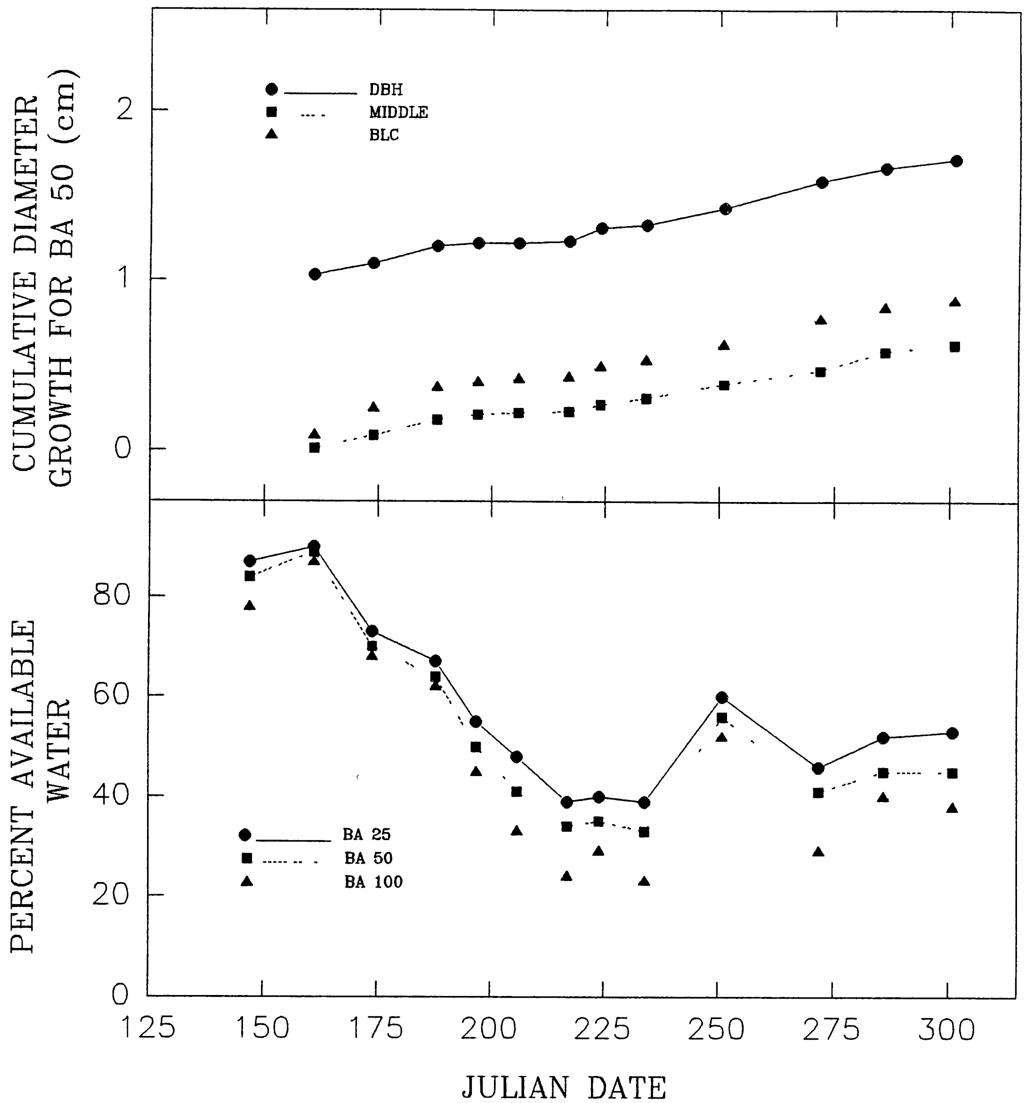

Figure 5 Percent available water and cumulative mean diameter growth of BA 50 at different bole heights

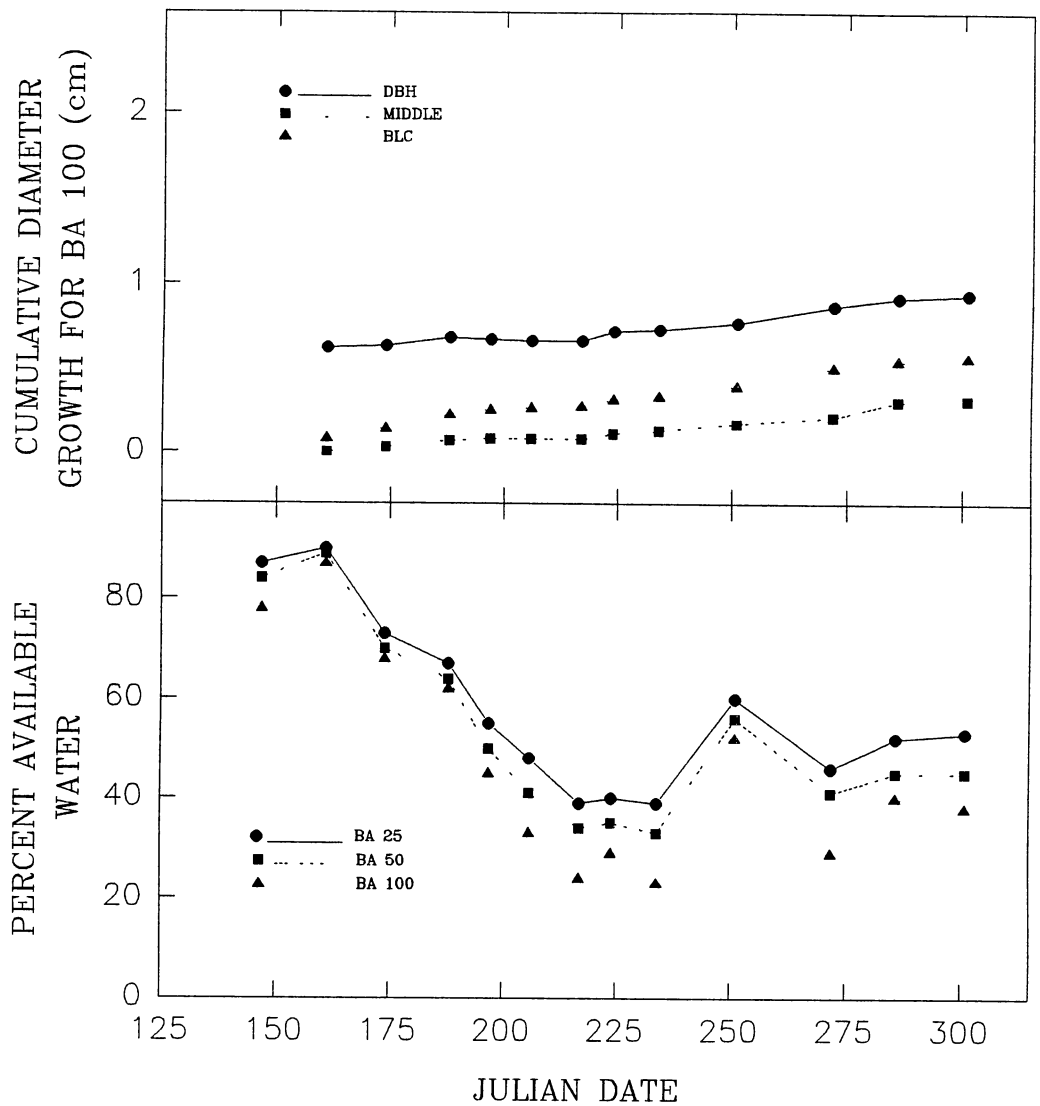

Figure 6 Percent available water and cumulative mean diameter growth of BA 100 at different bole heights.

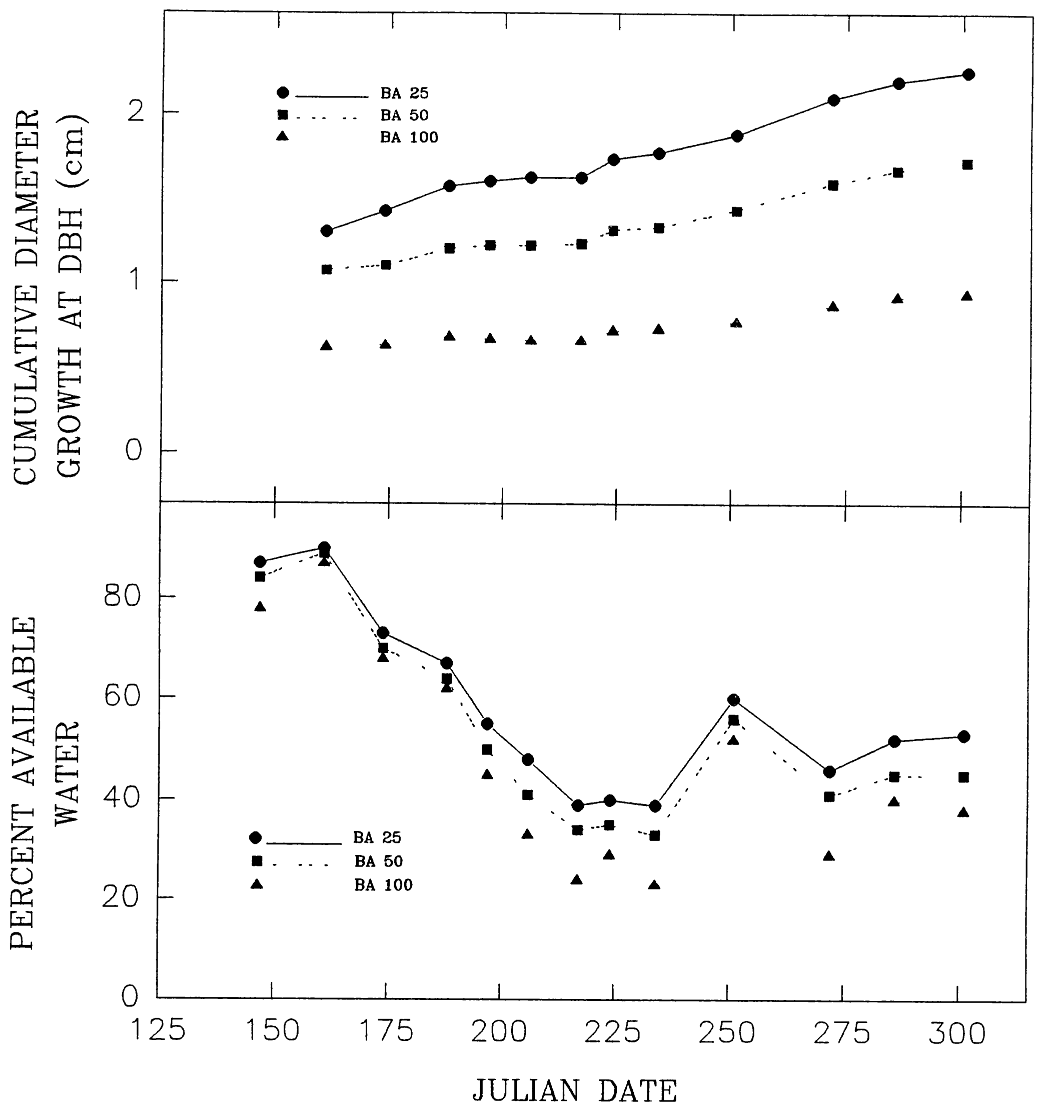

Figure 7 Percent available water and cumulative mean diameter growth at DBH for the BA 25, BA 50, and BA 100 treatments

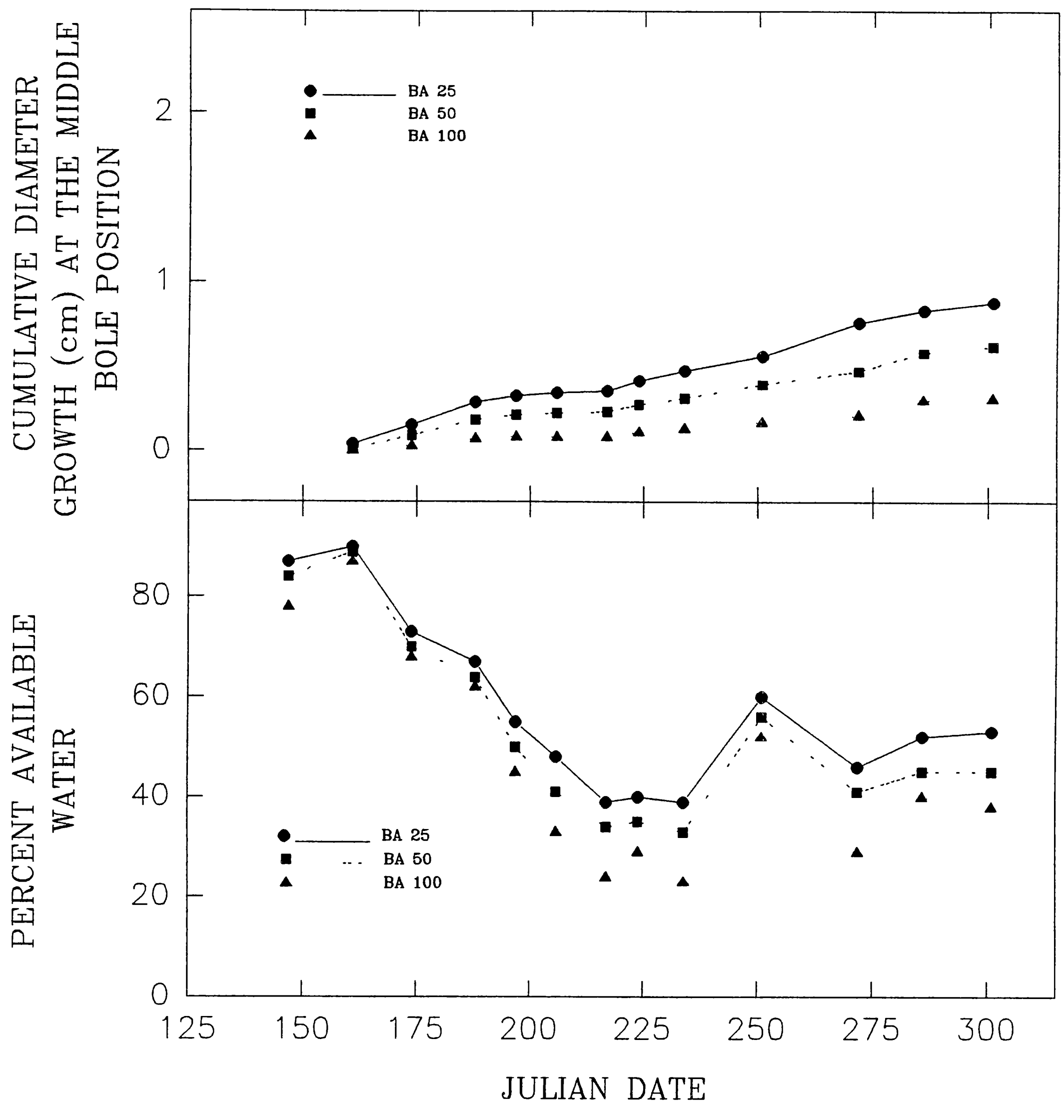

Figure 8 Percent available water and cumulative mean diameter growth at the middle bole position for the BA 25, BA 50, and BA 100 treatments.

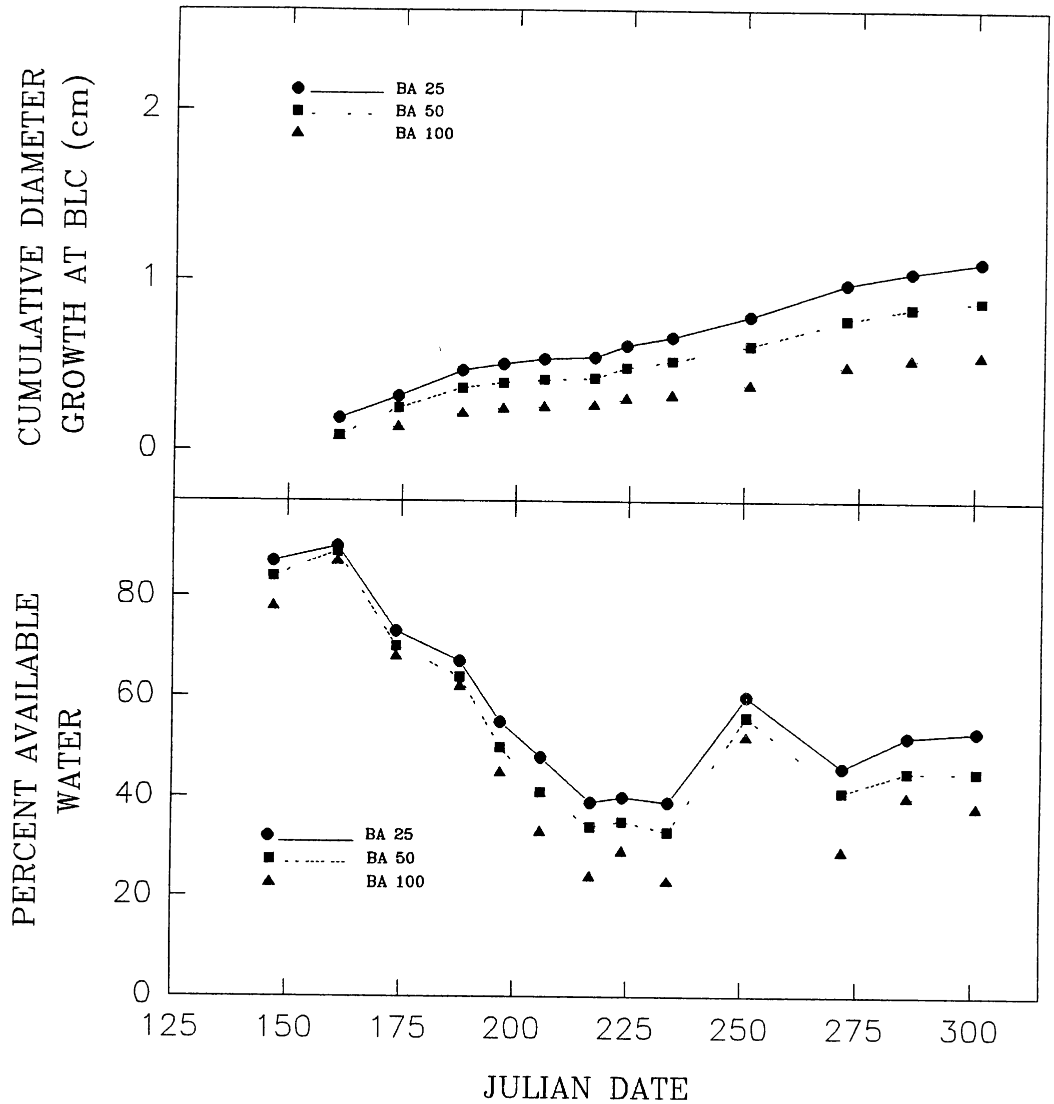

Figure 9 Percent available water and cumulative mean diameter growth at BLC for the BA 25, BA 50, and BA 100 treatments.

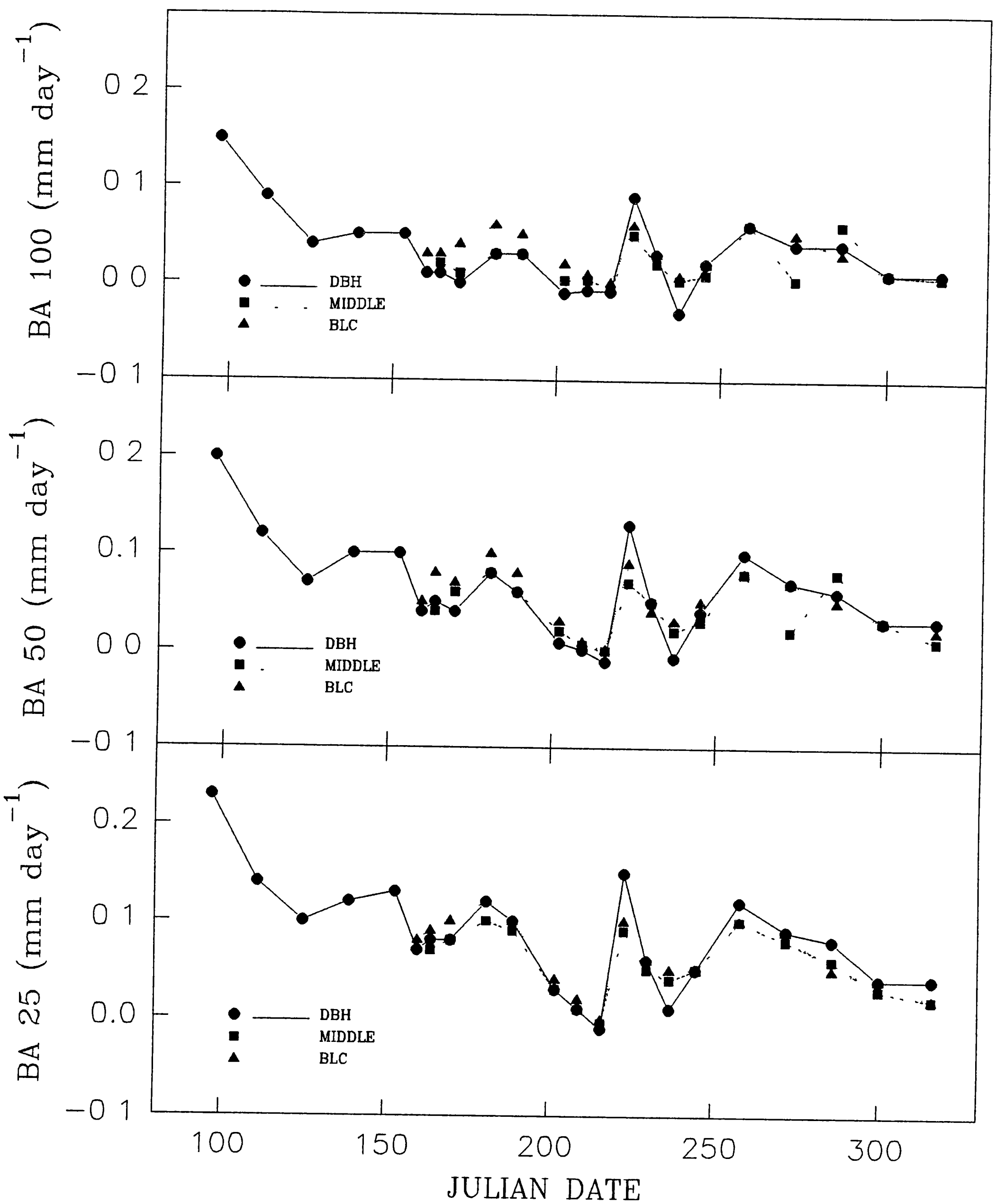

Figure 10 Mean daily growth rate of BA 25, BA 50, and BA 100 treatments at different bole heights N = 15.

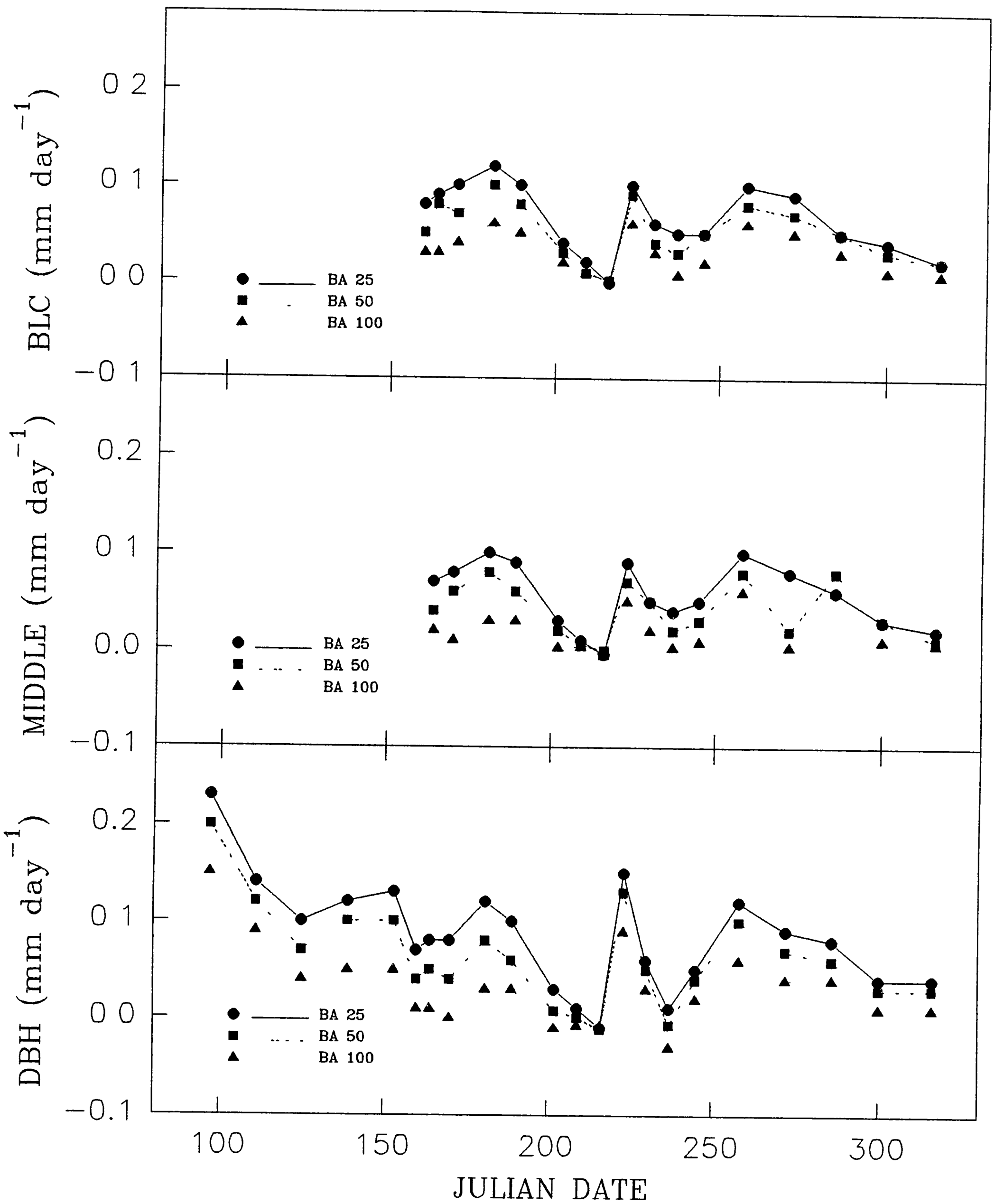

Figure 11 Mean daily growth rate of bole at the DBH, middle, and BLC positions for the BA 25, BA 50, and BA 100 treatments N = 15.

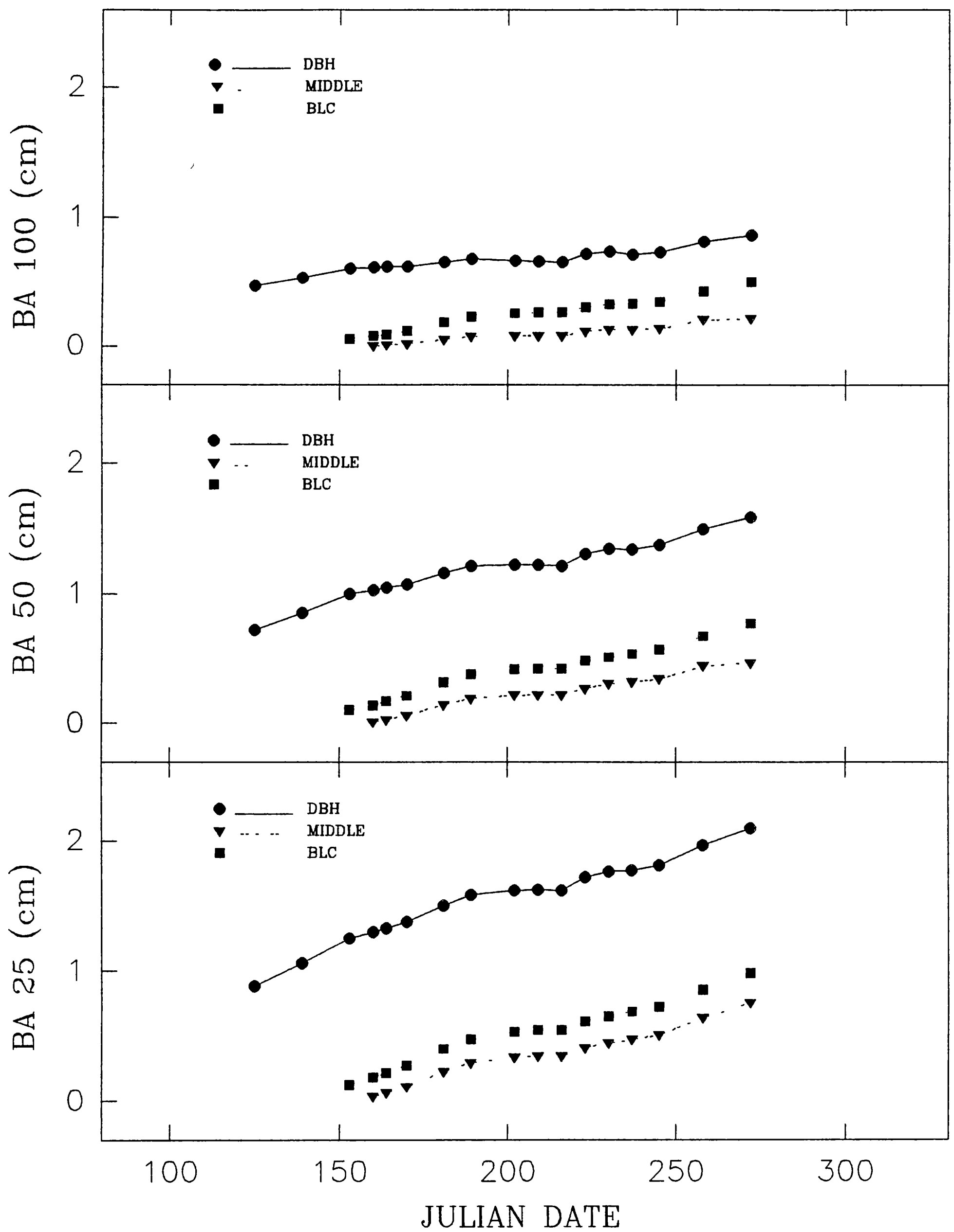

Figure 12 Cumulative growth of the BA 25, BA 50, and BA 100 treatments at different bole heights. N = 15.

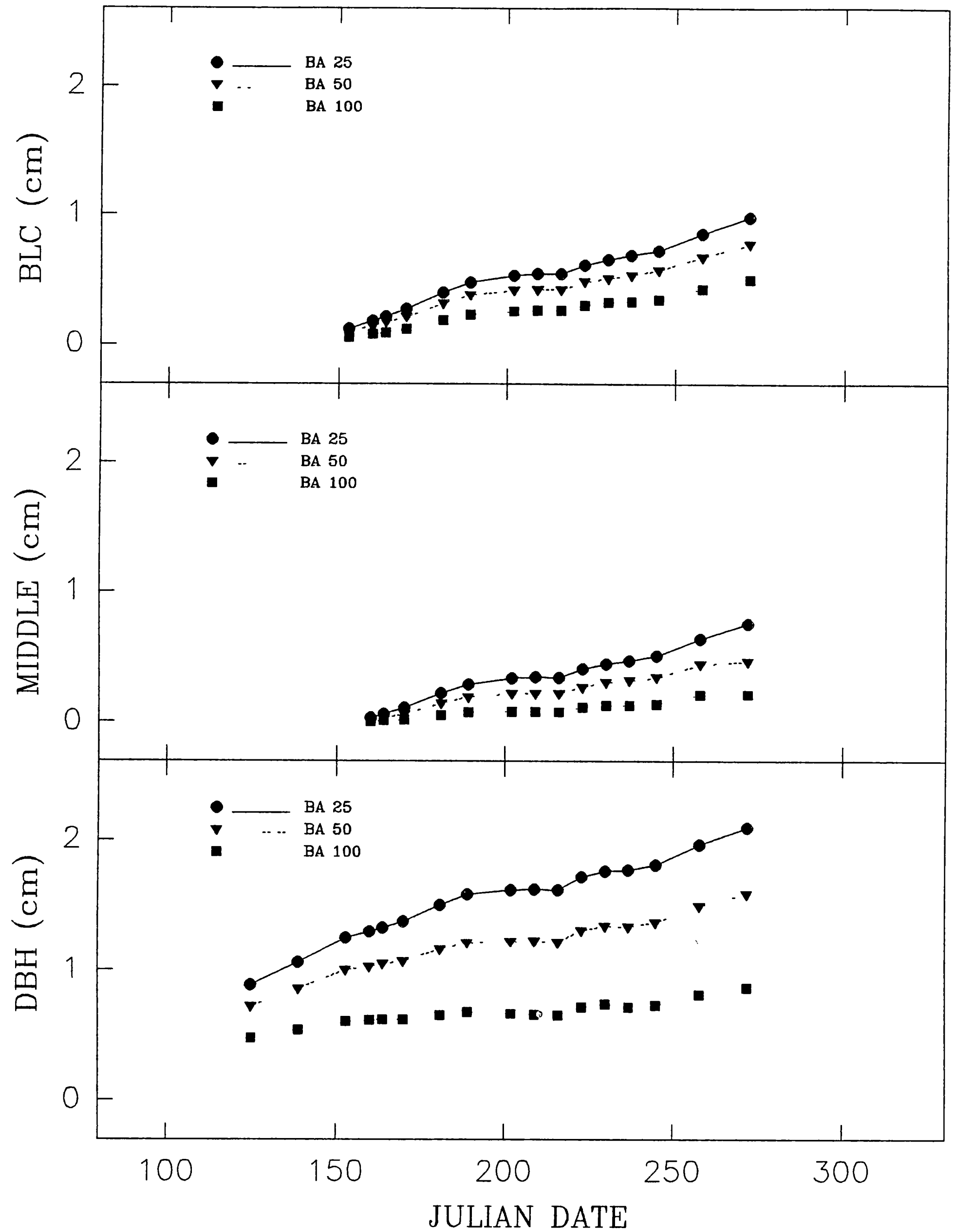

Figure 13 Cumulative growth of bole positions at DBH, middle, and BLC for the BA 25, BA 50, and BA 100 treatments. N = 15

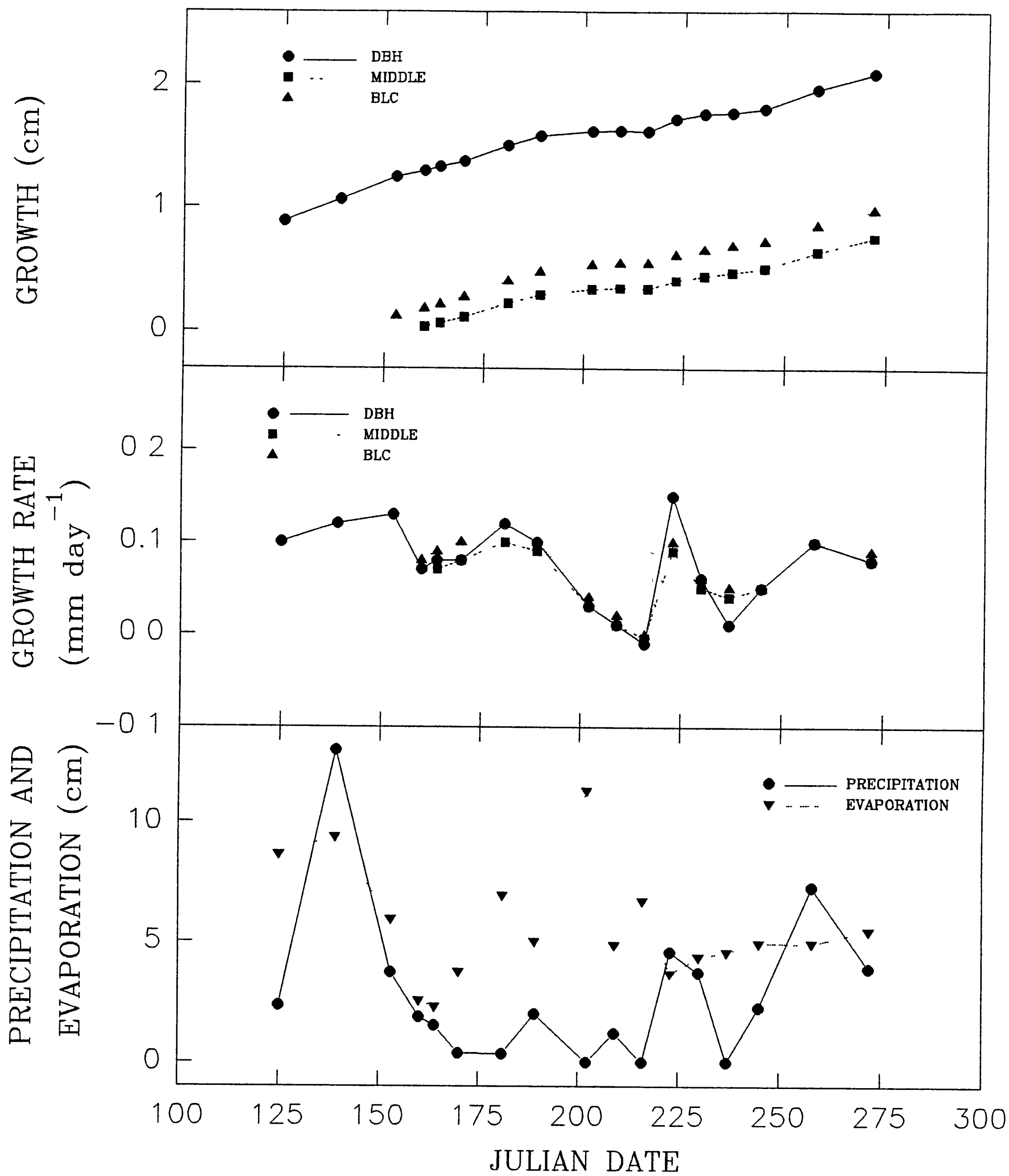

Figure 14 Precipitation, pan evaporation, mean daily growth rate and cumulative growth for all bole positions for the BA 25 treatment from May to October, in 1986 N = 15.

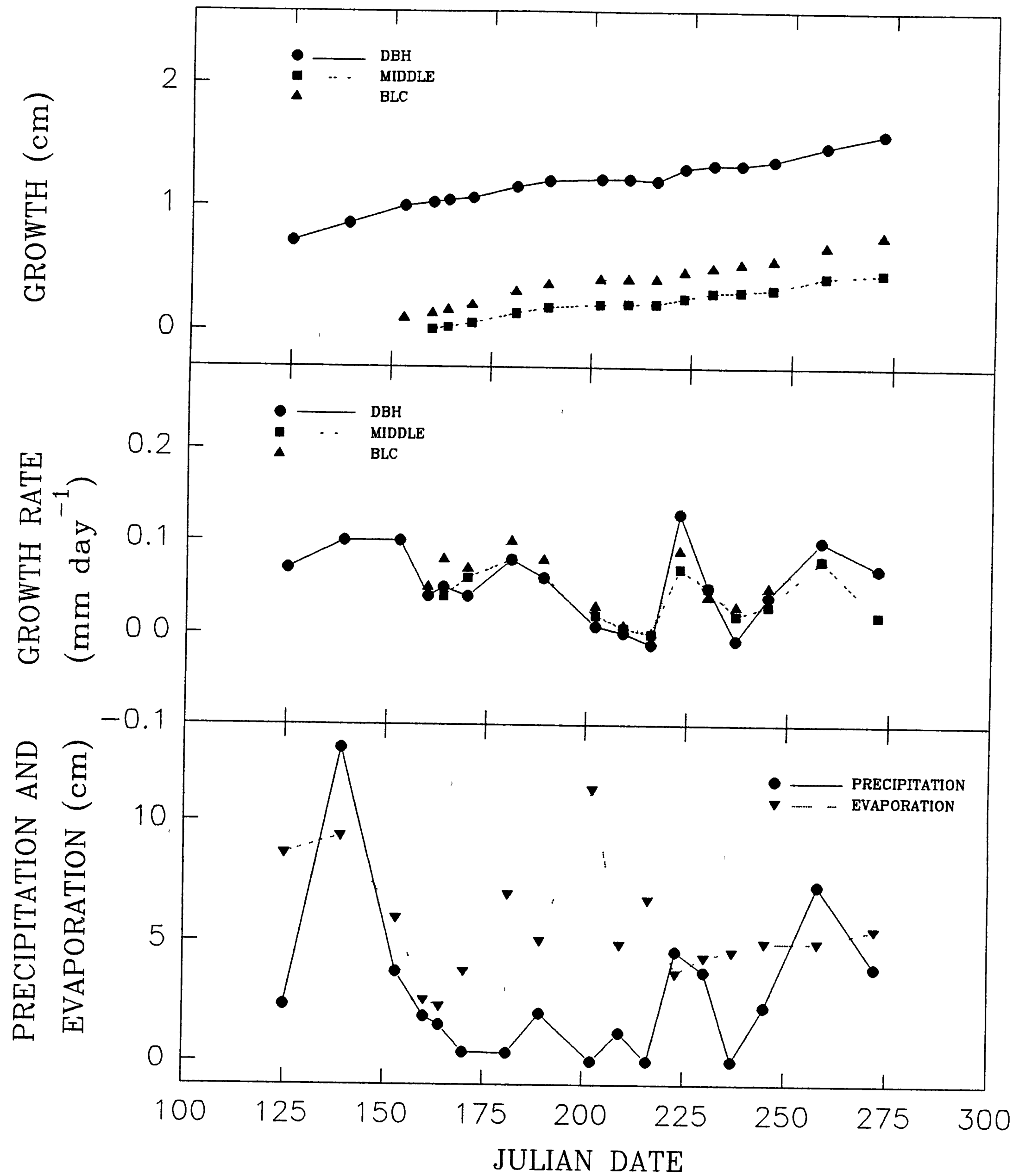

Figure 15. Precipitation, pan evaporation, mean daily growth rate and cumulative growth for all bole positions for the BA 50 treatment from May to October, in 1986. N = 15.

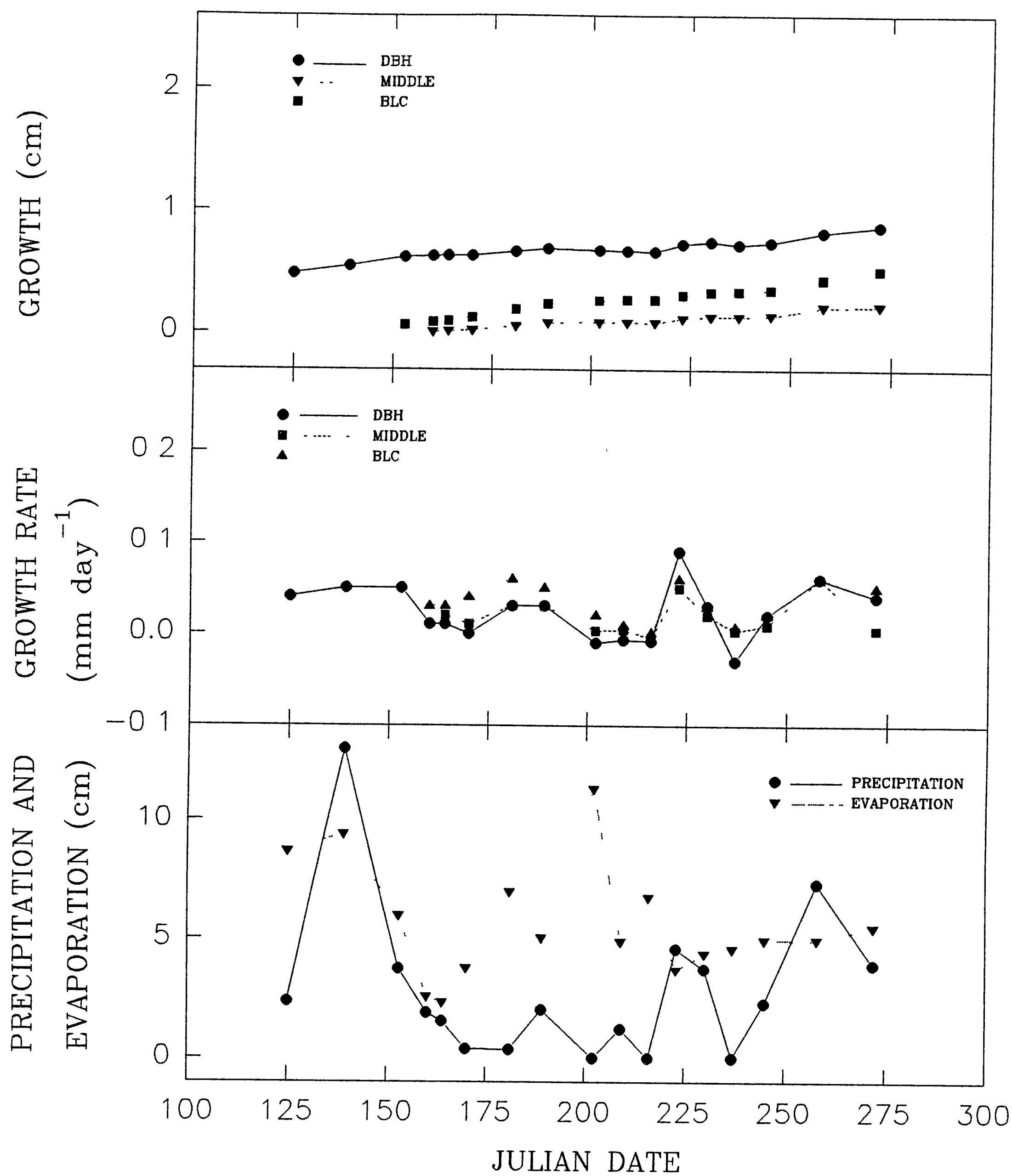

Figure 16. Precipitation, pan evaporation, mean daily growth rate and cumulative growth for all bole positions for the BA 100 treatment from May to October, in 1986 N = 15

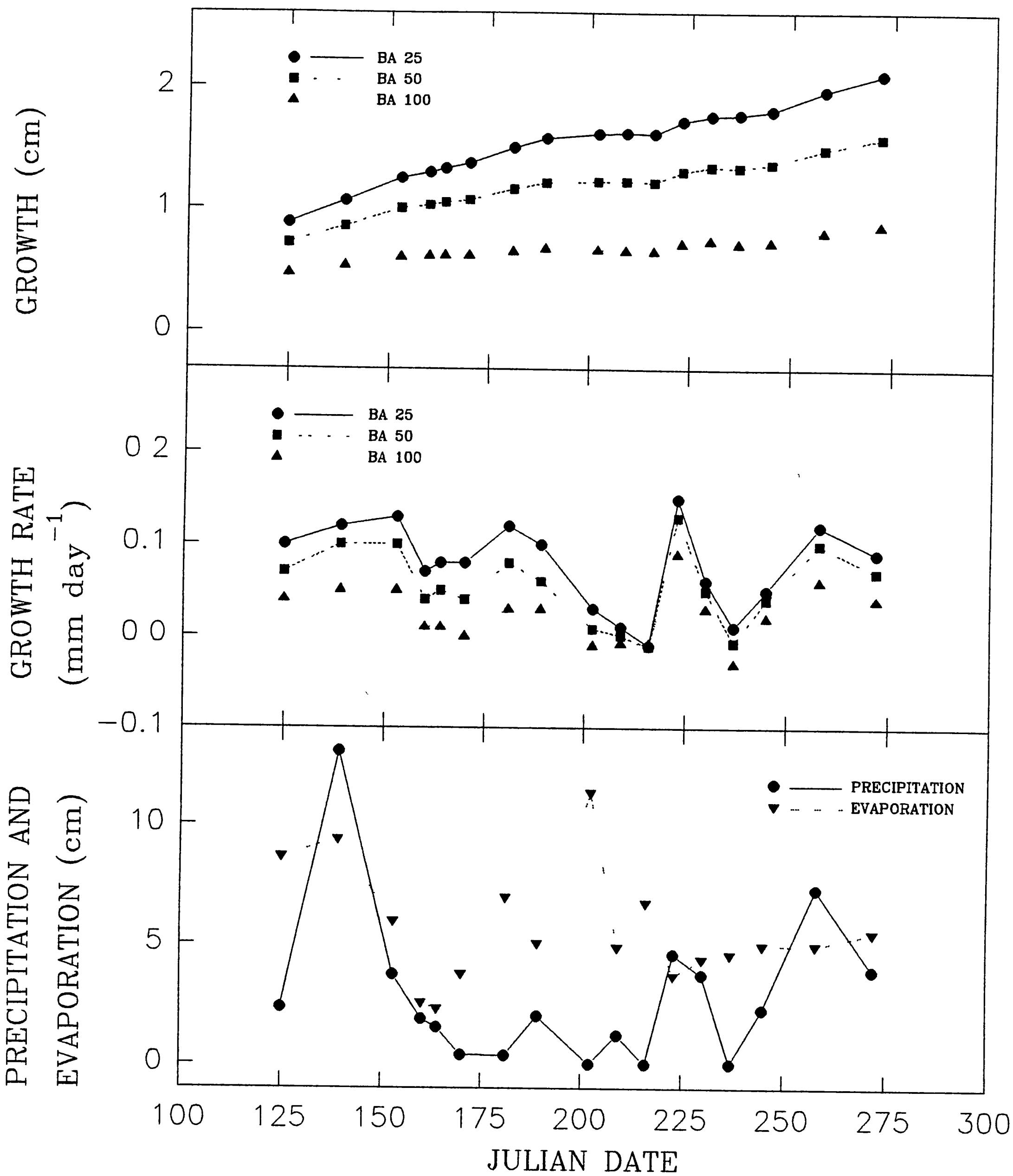

Figure 17 . Precipitation, pan evaporation, mean daily growth rate and cumulative growth for all the treatments at DBH from May to October, in 1986 N = 15.

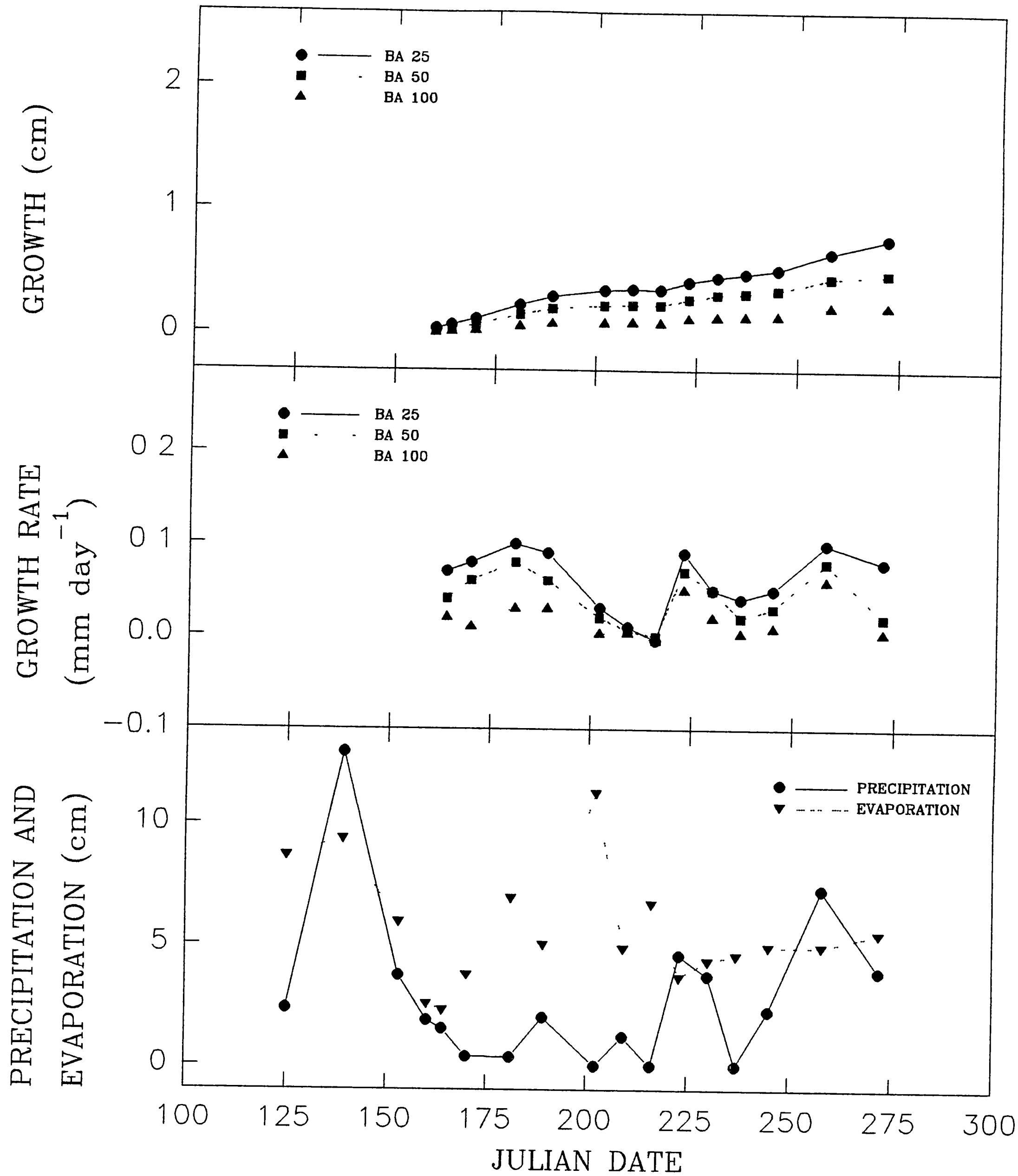

Figure 18 Precipitation, pan evaporation, mean daily growth rate and cumulative growth for all the treatments at the middle bole position from May to October, in 1986 N = 15

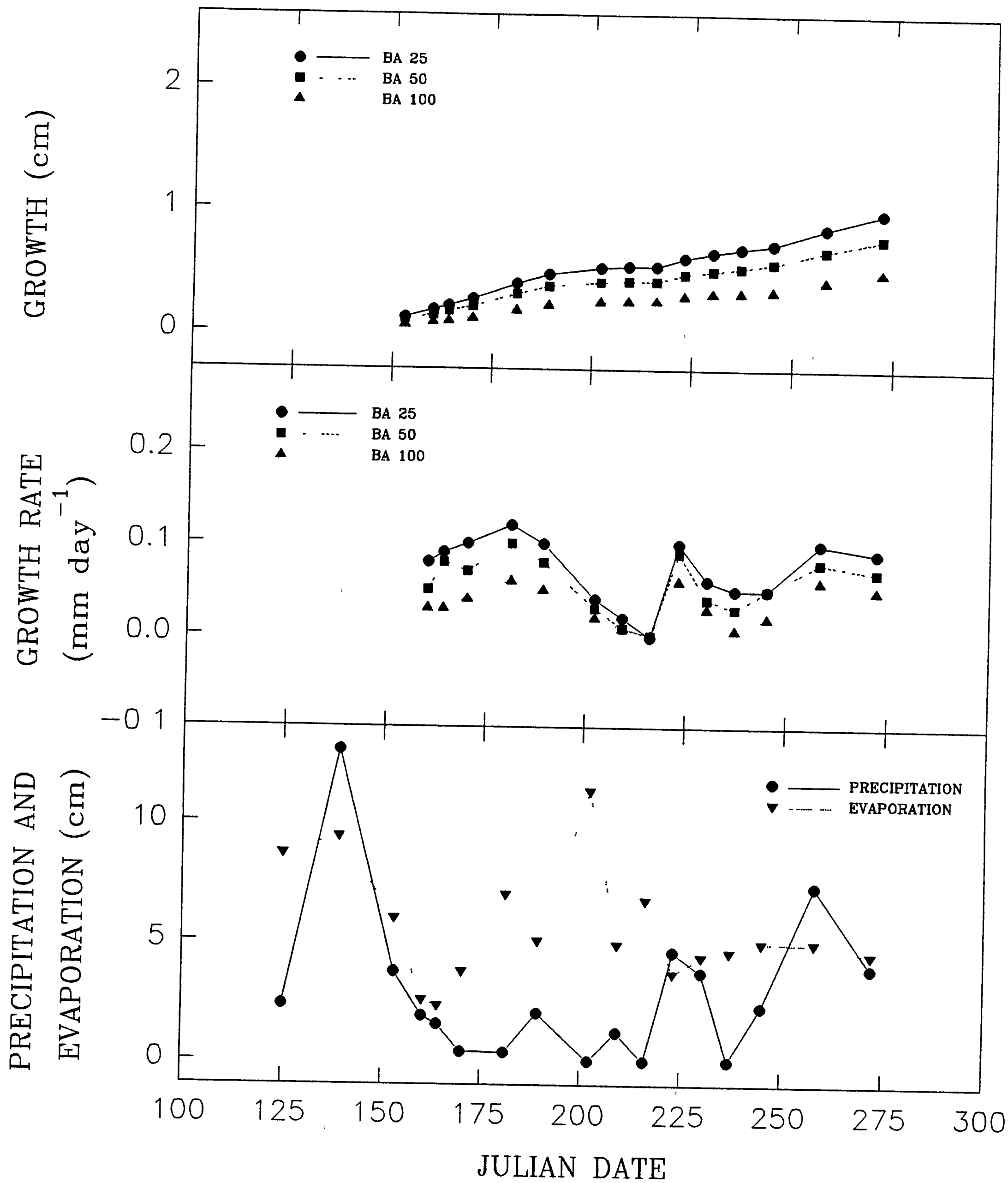

Figure 19. Precipitation, pan evaporation, mean daily growth rate and cumulative growth for all the treatments at the BLC bole position from May to October, in 1986 N = 15.

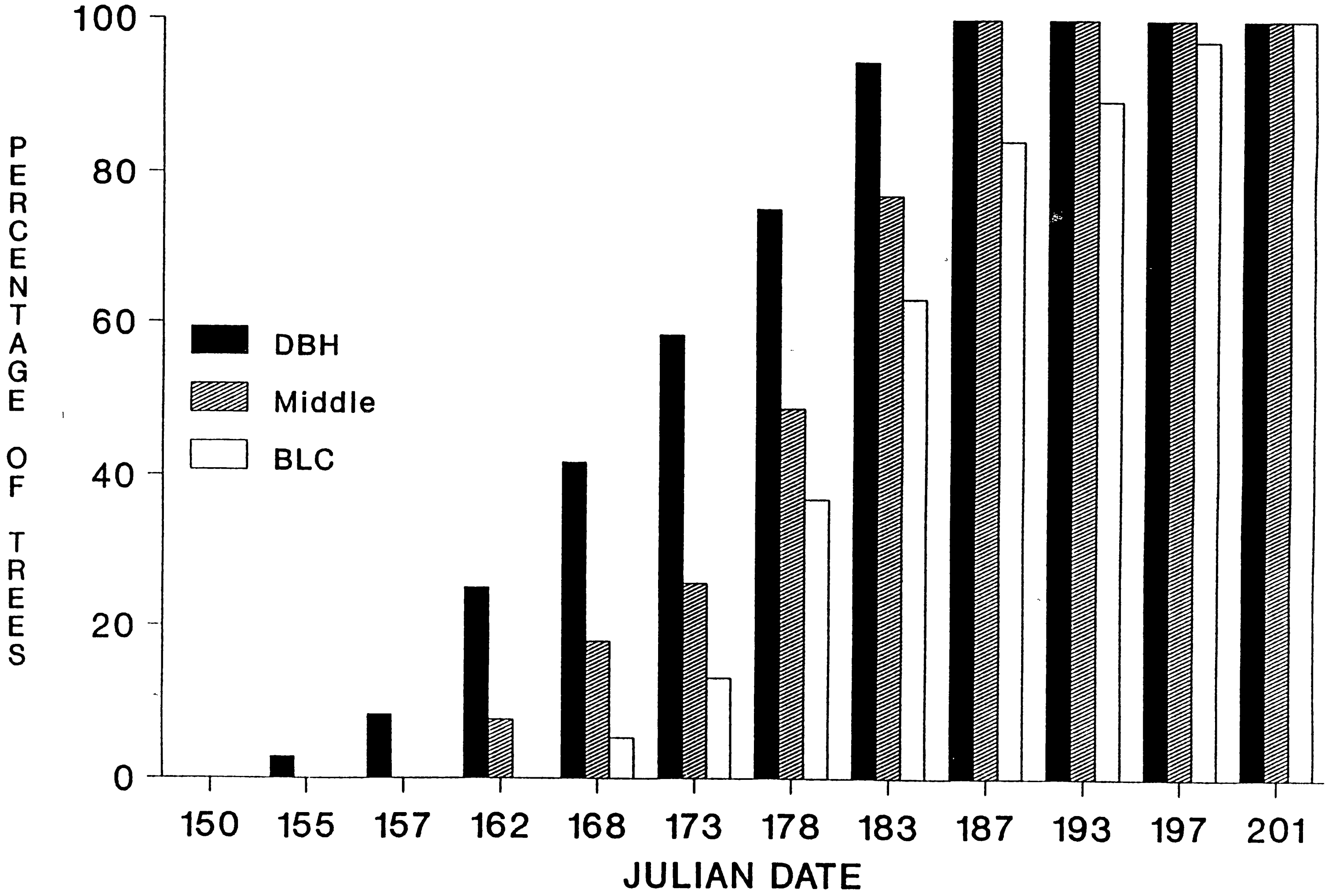

Figure 20. Cumulative percentage of trees past latewood initiation date at different bole heights, in 1986.

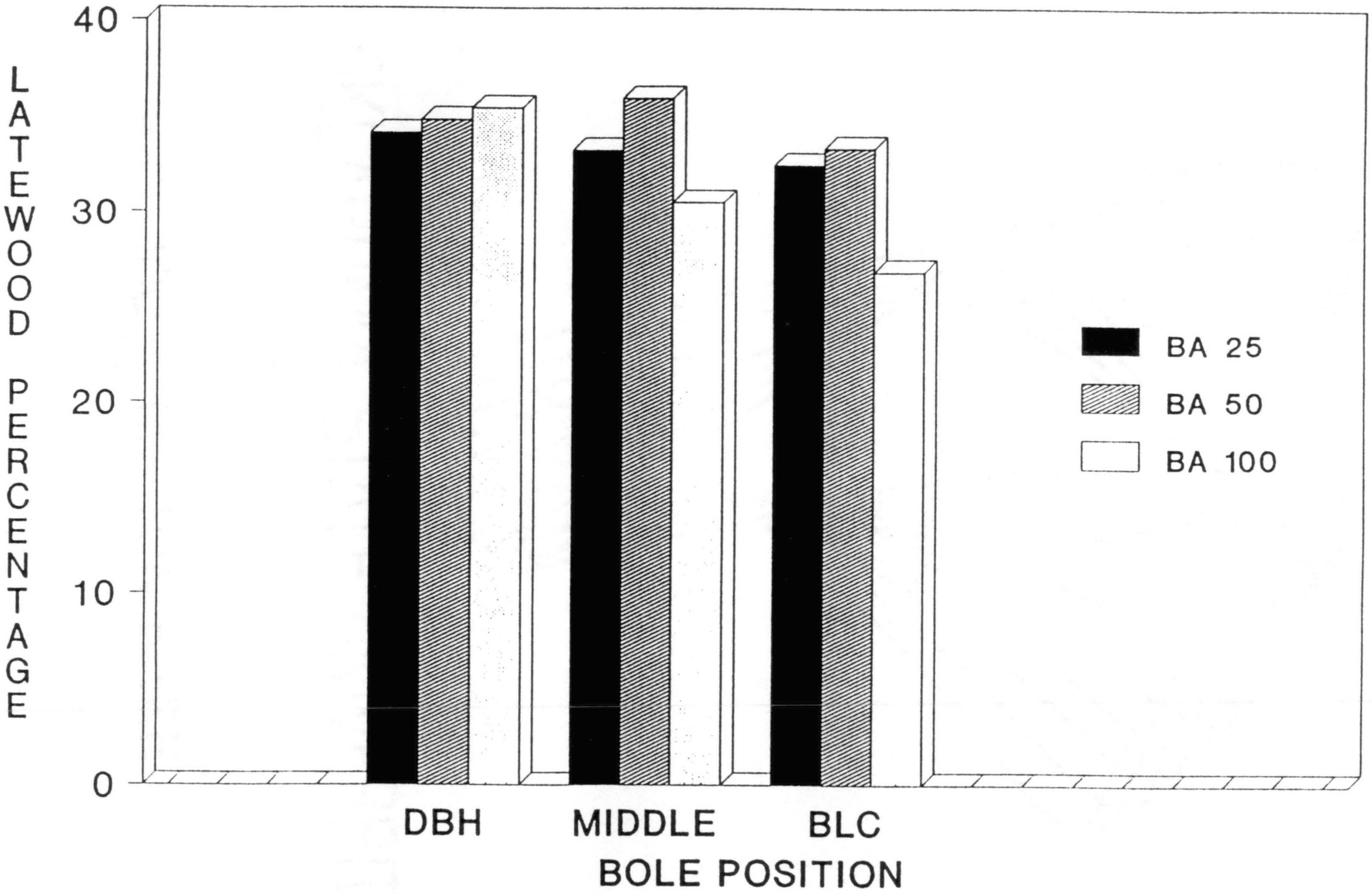

Figure 21. Mean latewood percentage by bole position for three stand densities.

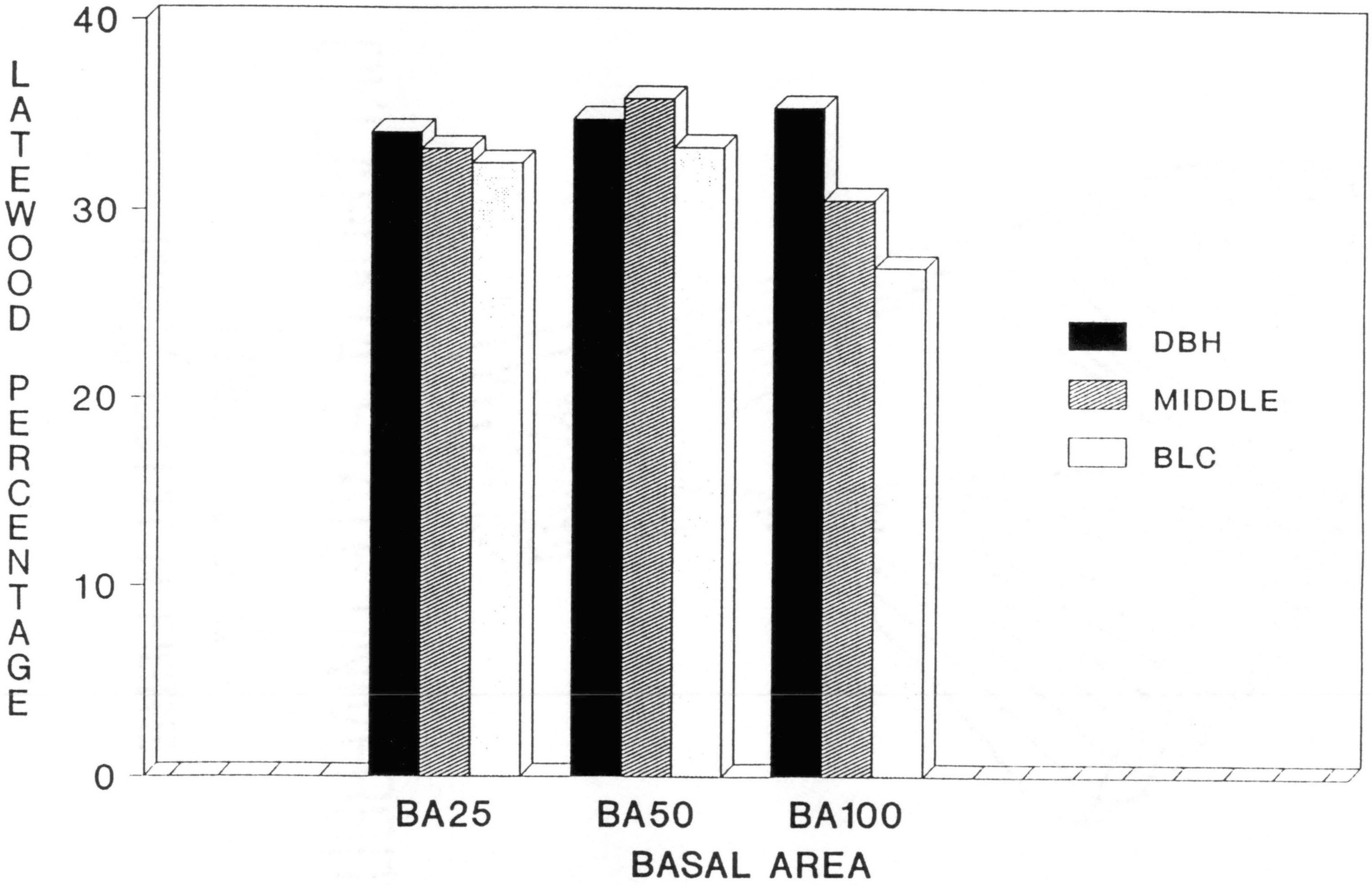

Figure 22. Mean latewood percentage within the thinning treatments for three bole positions.

VITA

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Candidate for the Degree of

Master of Science

Thesis: DIAMETER GROWTH AND WOOD PROPERTIES OF 14-YEAR-OLD LOBLOLLY PINE (Pinus taeda L.) IN RELATION TO STAND DENSITY AND CLIMATE

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